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The use of electrical resistivity measurement as a non-destructive test in precast concrete sleepers' production

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ABSTRACT: In the production of concrete sleepers, it is common to verify that the concrete has the necessary strength for prestress forces release by testing cylinders cured at equivalent conditions. Considering that electrical resistivity measurements may assess the pore structure evolution of concrete, this study proposes the use of this technique to estimate concrete strength evolution at factory conditions. The use of non-destructive testing methods considerably simplifies and modernizes the industrial process, leading to a reduction in labor time and waste. This paper presents a testing protocol aimed at obtaining correlation graphs between concrete compressive strength and electrical conductivity. As the temperature, size and shape of samples may be variable, this paper also presents an innovative procedure to assess correction factors. This procedure is suitable when the liquid water content is high enough not to influence the resistivity measurement. The proposed method was validated at a factory, showing a high correlation.

KEY WORDS: Concrete; Railway sleeper; Electrical resistivity; Non-destructive tests; Industrial production.

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RESUMEN: *La resistividad eléctrica como ensayo no destructivo en la producción de durmientes de hormigón*. En la prefabricación de durmientes de hormigón se suele verificar la resistencia necesaria para la transferencia de tensiones de pretensado ensayando probetas cilíndricas curadas en condiciones equivalentes. Dado que la medida de resitividad eléctrica refleja cambios en la estructura de poros, este trabajo propone utilizar la resistividad como estimador de la evolución de la resistencia del hormigón. La utilización de este método no destructivo podría conducir a un proceso productivo más simple y moderno, reduciendo los tiempos de trabajo y residuos. Este trabajo presenta un protocolo para obtener curvas de correlación resistividad – resistencia a compresión. Dado que la temperatura y la forma y tamaño de las muestras puede ser variable, este trabajo presenta un procedimiento innovador para obtener factores de corrección. El procedimiento es válido cuando el contenido de agua líquida es suficientemente alto para no afectar la medida de resistividad. El procedimiento fue validado en fábrica, mostrando buena correlación.

PALABRAS CLAVE: Hormigón; Durmiente Ferroviario; Resistividad eléctrica; Ensayo no destructivo; Fabricación.

1. INTRODUCTION

The present study aims to analyze the manufacturing process of one of the main elements of railway superstructure, the prestressed concrete sleepers, (1) and to propose the use of an innovative technique to make this process more sustainable.

Many international standards and manuals (2-10) show some differences in the requirements of the concrete sleepers, but they all follow the same guideline worldwide and the use of steam curing is widely used to improve the process productivity. After this accelerating curing cycle, the concrete should have the required strength to proceed with subsequent production stages, such as the release of the prestressing forces in the steel and demoulding. Should this strength be not enough, the sleepers may be damaged by the effort. Moreover, curing regime plays an important role in the evolution of pore structure, strength evolution and other key properties, such as durability (11). Actual concrete strength is assessed by testing concrete cylinders subjected to curing conditions equivalent to those of the structural element (12). This methodology requires casting a considerable number of paired samples, which involves a significant investment in labor hours and considerable waste generation.

Regarding sustainability, the concrete sleeper industry is not exempt from the reality of the construction sector, which is one of the largest emitters of greenhouse gas emissions (13, 14). For this reason, it is very important to analyze the production process in detail to evaluate different strategies for future optimization. Many authors have developed a carbon footprint analysis of Railway Sleepers made from different materials (15-17). For all sleepers, it is important to mention that service life is a decisive factor for the environmental profile (16) and that the impact of raw materials is higher than the technology used for sleeper manufacturing (17). Nevertheless, any effort on reducing carbon footprint and labor requirements at the production stage should be implemented.

Life cycle assessment (LCA) is a technique for compiling important inputs and output associated with a product and evaluating the potential environmental impacts (18, 19). Since the development of a Life Circle Assessment (LCA) of a concrete sleeper involves different aspects and may be complex to analyze all of them, the present study was only focused on some strategies that can be adopted in the manufacturing stage to obtain a more sustainable product, not only regarding environmental aspects, but also regarding cost and labor savings. For example, efforts focused on reducing waste generation (what reduce the quantities of raw materials), optimizing production times and improving the quality control could significantly contribute to this aspect.

In this line, it is well known that the evolution of the pore structure occurring at early ages induces changes in the electrical resistivity of concrete and affects strength evolution as well; thus, the absolute electrical resistivity may be used as an indicator of the concrete compressive strength. An interesting feature of this measurement is its non-destructive nature and the possibility of integration in the common quality control schema, making it applicable at any factory without inducing significant additional effort (20). Indeed, the number of cast cylinders may be strongly reduced.

The electrical conductivity of concrete is electrolytic by nature and, thus, it relates to the "mobility of ions" in the pore water of the concrete. Under saturation conditions, the pore structure influences the ion mobility, and connectivity and tortuosity play an important role (21). Once in the hardened state, as the hydration proceeds, the overall porosity is reduced, losing connectivity and increasing the tortuosity of the paths, which leads to an increase in the resistivity (22). Therefore, the electrical resistivity measurement is a tool to assess the degree of hydration in young concrete at the hardened state, where its porosity remains saturated (23).

There are different techniques for measuring electrical resistivity. For in-situ and laboratory measurements, resistivity meters with 4-point electrodes is used, according to the Wenner configuration. In particular, this test was initially developed to measure soil resistivity (24) and, more recently, it was adapted to perform measurements on concrete samples using a suitable portable device. Currently, the test is standardized by UNE-EN 12390-19:2023 (25).

For a given saturated sample, the electrical resistivity is an indicator of the concrete's transport capacity, and it is recognized as a durability indicator (26). In non-preconditioned samples, the results are highly dependent on the moisture content of the sample, and the measured value can significantly increase by orders of magnitude if the sample is partially dry (27). When this Non-Destructive Test is aimed at assessing the pore structure evolution, the humidity content of concrete should be over the percolation limit of the liquid water content (close to saturation).

Additionally, Presuel-Moreno and Liu (28) have analyzed the influence of sample temperature on the electrical resistivity of concrete, concluding that the obtained values decrease as the temperature rises. These authors have analyzed the behavior of samples up to a temperature of 45°C, which is lower than the typically used maximum curing temperature in factories. Regarding this matter, for example, the UNE-EN 13230-1:2016 (29) specifies 60°C as the maximum temperature of the concrete at the time of measurement. The range over 45°C and up to 60°C is crucial when assessing the application of the method in the manufacturing of prestressed sleepers subjected to steam curing cycles.

Another important issue to consider is the influence of the shape and size of the specimen, as related to the distance between the electrodes. In this regard, Morris et al. (30) have proposed dimensionless factors to estimate the absolute resistivity, the actual property of the material, from the apparent resistivity obtained through measurements with a Wenner device (Figure 1). More recently, Minagawa et al. (31) have undertaken a similar study, conducting experimental tests and comparing them with results obtained though numerical modeling, also incorporating and analyzing the correlation with prismatic specimens.

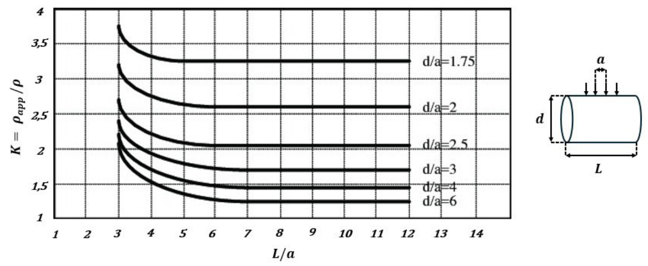

Figure 1. Adaptation of graph for Shape Factor (K) in measurements along the generatrix of the 15 cm x 30 cm cylindrical specimens (30).

When measurements are made on samples different from cylinders, as for example in a concrete sleeper, the Shape Factor (K) (actually, it should be size and shape factor) is uncertain. This paper introduces a practical method to assess this factor for any shape and size.

Finally, Garzon et al. (32) have demonstrated that the presence of steel bars in measurements conducted on reinforced concrete can potentially alter the measurement, depending primarily on the orientation of the measuring equipment with respect to the main reinforcement and the thickness of the cover.

Regarding its applications, the measurement of resistivity is used as an indicator of the potential durability of concrete. In this field, some authors (26, 33-36) have studied the correlation between concrete resistance to chloride ion penetration and electrical resistivity. Indeed, there is an AASTHO Standard that gives a direct link between the resistance to chloride ingress and the electrical resistivity (37). In addition, another study proved that the measurement may be suitable for the in-situ assessment of drying processes (27).

Moreover, there is experimental evidence (38, 39) suggesting that there exists a correlation between electrical resistivity, maturity and compressive strength of concrete, a correlation that could be used to estimate the evolution of mechanical properties on an industrial scale under variable temperature regime. However, it would be necessary to identify the shape and size coefficient that relates the apparent resistivity (measured by the instrument) to the absolute resistivity. Moreover, in the case of manufacturing processes with steam curing, the influence of temperature on the apparent resistivity should also be considered.

Aimed at developing the application of electrical resistivity measurement in early-age concrete as an indicator of mechanical resistance evolution in steam curing cycles (i.e. maturity increase), it was necessary to validate some hypotheses.

The first hypothesis states that the correlation between concrete compressive strength and electrical resistivity measured by Wenner method on saturated standard specimens is highly satisfactory (greater than 0.90) measured at laboratory temperature.

The second hypothesis states that, at a very early age and under saturated conditions, the electrical resistivity depends on the mobility of ions, which increases with concrete temperature. As a result, a "temperature correction factor" can be determined to uncouple the influence of temperature on apparent resistivity.

Finally, the third hypothesis states that the relationship between the apparent resistivity and the absolute resistivity of concrete, a true "material property", depends on the specific design of the Wenner probe (electrodes separation) and the dimensions (size and shape) of the sleepers under measurement; this coefficient is known as "size-and-shape correction factor" and can be assessed experimentally by means of a suitable testing calibration protocol.

The application of this method on an industrial scale offers numerous advantages as compared to current control procedures. From the perspective of labor performance, adding a predictive method for compressive strength is expected to provide greater accuracy in assessing the earliest time to stresses transfer from steel to concrete and, consequently, a reduction of the number of tests in compression can be expected. As a result, this would not only lead to a more efficient process, by optimizing production time, but to contribute to material savings and a reduction in waste, which mitigates the environmental impact of the industry, especially when portland clinker based cements are involved. Finally, the methodology could provide greater safety to the production process and higher quality to the finished product, by decreasing the risk of noncompliance with the specified strength at a given stage of the process.

2. METHODOLOGY

The applied methodology is experimental and aims to calibrate the assessment of the compressive strength under variable curing conditions by using a non-destructive method based on electrical resistivity measurement of concrete using a Wenner probe. Once the correlation is proven, it also seeks to assess the correction factors due to geometric aspects (shape and size of the element and electrodes separation in the Wenner array) and the correction factor associated to variations in temperature. For the realization of the present study, the Wenner probe had a separation between electrodes of 38 mm. For each measurement, at least 3 (three) readings were made with the resistivity meter at different generators of cylindrical samples and the average value was considered as the “apparent” resistivity. In some cases, these readings were equal, and no standard deviation could be assessed. Indeed, a “global” standard deviation was calculated for the whole set of specimens, assuming that the coefficient of variation (CV) was constant. Then, the S for each reading was calculated. The calculation of a global variance was not considered because the range of the resistivity readings is too wide.

The overall approach is based on conducting experiments at laboratory where the following variables were decoupled, using samples with different sizes and dimensions (Figure 2):

- To decouple the influence of temperature on resistivity, all measurements not involving thermal cycles were conducted in a laboratory at a constant temperature of 23°C ± 3°C.
- To determine the influence of the size and shape of the tested element on the results, simultaneous and comparative measurements of electrical resistivity were taken on cylindrical specimens of 10 cm in diameter and 20 cm in height, on cylindrical specimens of 15 cm by 30 cm, and on prismatic elements of 15cm by 15cm by 30cm in length. The use of a prismatic sample aimed at being comparable to a cross section of a concrete sleeper.
- To analyze the influence of the temperature on resistivity measurements, different sets of results were obtained on samples subjected to stable thermal conditions, in addition to the standard temperature at the lab.

Finally, once the intrinsic correlation and the corresponding coefficients were assessed, the method was validated at industrial conditions in a sleepers’ factory, by conducting electrical resistivity measurements on pre-stressed monoblock concrete sleepers (Figure 3) with metric gauge (1000 mm) and on cylindrical and prismatic samples that were cast with the same concrete.

Figure 2. Samples for laboratory method calibration.

Figure 3. Pre-stressed concrete sleeper for industrial scale validation.

Figure 4. Measurement of electrical resistivity on a cylindrical specimen.

3. MATERIALS AND CONCRETE SAMPLES

Concrete constituents were equivalent to the ones used by the sleeper industry, aimed at guaranteeing the comparability between the laboratory and factory stages. A standard 60 MPa mix was prepared, using a CPN 50 (equivalent to CEM I 52.5), siliceous coarse aggregate, natural sand and crushed sand and a polycarboxylate based superplasticizer. Mixture proportions are shown in Table 1.

Table 1. Concrete mix proportions of H-60 concrete.

Concrete mixture proportions for aggregates in the SSS condition (kg/m3)	
Cement (CPN 50)	380
Fine natural sand (H=3.3%)	556.2
Crushed sand (H=0.9%)	301.8
Coarse aggregate (6-20)	948
Water	139
Polycarboxylate based superplasticizer	1.5

Table 2. Characteristics of concrete mix.

Characterization	Result
Slump	14.5 cm
Air content	3.0 %
Density (Unit weight)	2454 kg/m^3
3 days-compressive strength	47.4 MPa
28 days-compressive strength	65.9 MPa

The concrete was tested at the fresh state and at the hardened state in compression. Test results are given in Table 2. Once the results were compliant with the required strength and fluidity, different batches were prepared to cast the samples.

Note: The correlation between Compressive Strength vs Absolute Resistivity was checked for different concrete strengths; in each case, the correlation is different but the R^2 is always better than 0.95, (i.e., 0.98 for the 40 MPa concrete) providing more confidence to this relationship. This issue allowed reducing the number of samples to assess this correlation.

4. RESULTS AND DISCUSSION

4.1. Correlation between the maturity, electrical resitivity and compressive strength

The electrical resistivity was measured (Figure 4) at different time intervals (6 hours, 12 hours, 1 day, 2 days, 3 days, 4 days, 7 days and 28 days) on a reference specimen (H60-PR1) to avoid inter-sample variations. Moreover, additional samples were tested in compression at fixed intervals (samples H60-P1 to H60-P10). In this case, the intersample variation arises but, as the compressive strength test is destructive, there is no way to solve this issue. All samples were cured under water in standardized conditions (23°C) until the age of testing and were in saturation condition at the time of tests, according to IRAM 1546 (equivalent to UNE-EN 12390-3:2009).

In Figure 5, the relationships between maturity and electrical resistivity and between maturity and compressive strength are plotted. The uncertainty, calculated with a k=2, is indicated as error lines.

The figure shows that both curves follow a logarithmic law, with an greater than 0.96. As a consequence, it can be confirmed that both electrical resistivity evolution and concrete strength increase rate are influenced by the same factors. It is important to mention that the plot shows the results for the first 70 hours, as the control of compressive strength in manufacturing processes typically does not exceed this time. However, the analysis was extended to the first 28 days at standardized temperature, revealing that both relationships continue to conform to a logarithmic pattern, with an value exceeding 0.90.

4.2. Correlation between the compressive strengh of concrete and electrical resitivity

To complement the previous measurement, the electrical resistivity and compressive strength of the concrete were measured at different time intervals (6 hours, 12 hours, 1 day, 2 days, 3 days, 4 days, 7 days and 28 days) on all specimens (H60-P1 to H60-P10) that were under standard curing. To improve the assessment of the correlation between electrical resistivity and compressive strength, only paired values were considered, to eliminate inter-sample variability.

In Figure 6, the trend line that better adjusts test results determines the relationship between compressive strength and absolute electrical resistivity for H60 concrete. In line with what is indicated in the bibliography, the relationship between compressive strength and absolute electrical resistivity of concrete follows a logarithmic law, with an greater than 0.99, which validates the first hypothesis proposed. Next steps aim to isolate the results from the size and shape of the tested sample and from the measurement temperature, in order to calibrate at laboratory a methodology suitable for quality control at industrial scale.

This high degree of correlation may be due to the fact that the correlation was obtained from concretes of same composition. When either the strength or the cement composition is changed, the correlation is meaningless, according to Ali Akbar Ramezanianpour et al (35). This fact highlights the importance of developing the procedure for each concrete composition at the precast plant, as differences in proportions or materials may lead to an increase of uncertainty.

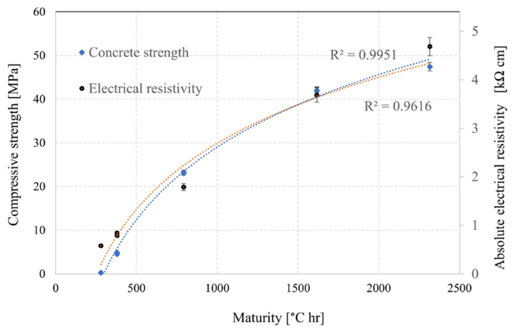

FIGURE 5. Relationship between maturity, electrical resistivity and compressive strength.

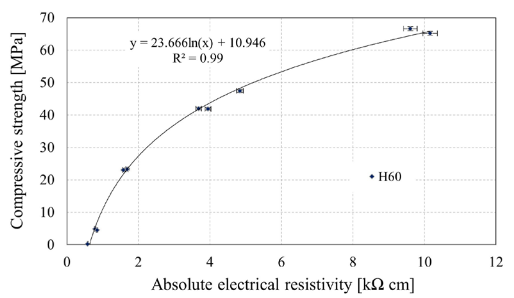

FIGURE 6. Relationship between compressive strength and absolute electrical resistivity of concrete.

4.3. Influence of the size and shape of the tested element

To assess the influence of the size and shape of the specimen on the measurement of electrical resistivity, the results of measurements over time for 10cm by 20cm cylindrical specimens, 15cm by 30cm cylindrical specimens and prismatic blocks 15cm by 15cm by 30cm in length were compared. All samples were cast with the same H60 concrete. The variation of the apparent resistivity values over time were analyzed and the results show that all curves follow a logarithmic trendline, with the lowest corresponding to the test conducted on cylindrical samples of 10cm by 20cm and exceeding 0.97.

According to Morris et al (30), absolute resistivity of 15 cm by 30 cm cylindrical samples can be assessed from the apparent resistivity obtained using the Wenner probe, by using a shape-and-size correction factor. As the absolute resistivity is a material property, it should be independent of the size and shape of the sample measured. Thus, the corrective factors for other shape and size samples can be calculated as follows: the values obtained for 10cm by 20cm cylindrical samples and for 15cm by 15cm by 30cm in length prismatic samples are divided by the values obtained for 15cm by 30cm cylindrical samples. Following this procedure, the graph plotted in Figure 7 is obtained. It is important to consider that this analysis has been limited to the first 100 hours, as the control of compressive strength in manufacturing processes typically does not exceed this time.

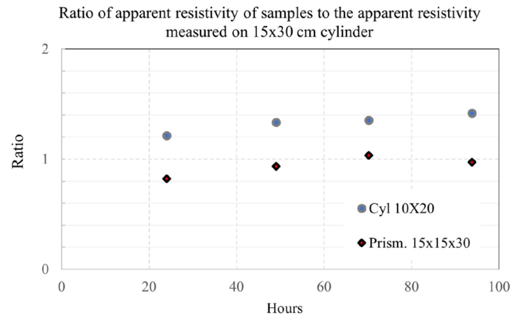

Figure 7. Relationship between apparent electrical resistivity of concrete and curing hours for different geometries.

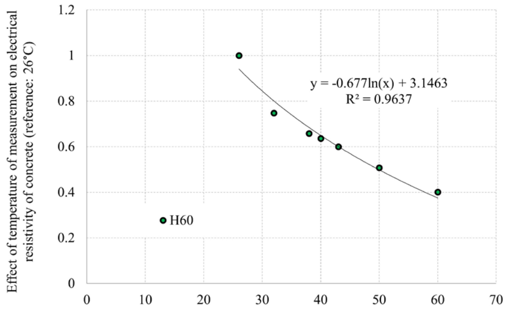

Figure 8. Relationship with electrical resistivity at 26 °C.

From the Figure 7, it can be observed that the obtained relationships show a constant trend, consistent with finding from other authors (30, 31), not only for a cylindrical specimen but also when the shape size of the sample is changed to a prismatic one, similar to the shape of a sleeper.

To validate the conducted experiment, the obtained results were compared with the theoretical values obtained using Morris et al.'s chart (30) and values reported by Minagawa et al. (31) for cylindrical specimens. From Morris et al.'s chart (30), approximate values of K – considering a tip spacing of 38 mm – are 1.9 and 1.35, respectively for cylindrical specimens of 10cm by 20cm and 15cm by 30cm. Thus, the ratio between these factors – and consequently the ratio between the apparent electrical resistivity of each specimen – is equal to 1.41. Moreover, from the results presented by Minagawa et al. (31), this coefficient is 1.35. Finally, it is observed from Figure 7 that the average of the experimentally obtained results for this relationship is 1.32 for cylindrical specimens of 10cm by 20cm, differing less than 5% from the aforementioned values.

In conclusion, if measurements at an industrial scale are conducted on the 10cm by 20cm cylindrical samples that are molded for estimating strength before prestressing forces release, it would only be necessary to apply the obtained correction factor. Additionally, in order to perform measurements directly on a railway sleeper, an experimental correction factor should be obtained in an equivalent manner.

4.4. Influence of the sample temperature at measurement

To assess the influence of temperature on electrical resistivity measurements, concrete samples were kept in thermal baths, which increased their temperature at fixed intervals; resistivity measurements were taken at these temperatures' steps. Between each step, samples were allowed to rest at a constant water temperature for one hour. Then, it is assumed that the temperature measured in the water was equal to the temperature within the mass of concrete samples. It is important to consider that the used samples had more than 90 days of curing, ensuring that any variation in the electrical resistivity was solely due to temperature changes and not to material strength evolution. Moreover, in line with the objective of this study, measurements were conducted up to a maximum temperature of 60 °C, consistent with the curing temperatures typically used in manufacturing. Additionally, the initial temperature of the test was 26°C as it was the standardized curing temperature for the specimens.

The results show that the relationship between the measurement of electrical resistivity and the increase in temperature follows an exponential trend, in line with literature. Assuming that the electrical resistivity value at 26 °C is equal to one, the ratio between the measured values at different temperatures and this reference resistivity are shown in Figure 8.

From the graph, it can be observed that the relationship follows a logarithmic trend with a greater than 0.96. Thus, it can be concluded that, as it occurs with the influence of the size and shape of the sample, an experimental correction factor can be identified to take into account the influence of the sample temperature on the electrical resistivity.

4.5. Application of the resistivity method at industrial scale

The calibrated method was tested on sleeper samples manufactured in the factory (Samples A and B). Sleepers were produced on a self-supporting bench with a single mould, using materials typically employed in the factory and following the usual manufacturing process. The curing of sleepers was not accelerated, so therefore, the samples were kept at ambient temperature throughout the entire process.

For the present study, sleepers, cylindrical and prismatic samples remained covered with a plastic tarp to ensure that all elements have enough humidity at the moment of measurement to overcome the threshold level of percolation for liquid water, despite the eventual external and internal drying due to hydration.

Before the application of prestressing forces, electrical resistivity measurements were taken on cylindrical samples of 10cm by 20cm, on prismatic samples of 15 cm by 15 cm and 30 cm in length and on the two sleepers. Additionally, compression tests were conducted on the 10 cm by 20 cm cylindrical specimens and the compressive strength of concrete was recorded. The average results of the compression tests, electrical resistivity and measured temperatures are presented in Table 3. It should be mentioned that although all elements were cured under the same conditions, the measured temperatures are different since cylindrical and prismatic specimens were inside the laboratory of the factory before testing (standardized temperature), while the sleepers were inside the factory at all times.

Table 3. Results of parameter measurements in factory.

Sleeper	Hours of curing	Measurement Temperature (°C)	Type of sample	Elect. Resist. (kohm cm)	Compres. Strength (MPa)
A	15.25	25.6	Cyl 10x20	2.45	16.73
			Prism. 15x15x30	1.75	-
		29.5	Sleeper	2.05	-
B	18	25.4	Cyl 10x20	3.10	20.37
			Prism. 15x15x30	2.2	-
		28.7	Sleeper	2.35	-

4.5.1. Correction of results based on size and shape factor

For adjusting values by the shape and size, the laboratory calibration coefficient performed previously was considered. No corrections for temperature have been made since only the test conducted on the cylindrical and prismatic specimens were considered for the present analysis.

Since 15cm by 30cm cylindrical samples have not been molded in the factory, values for the 10cm by 20cm cylindrical samples were considered as a reference and adjustment coefficient were applied to estimate electrical resistivity of prismatic specimens. Then, Table 4 compares the mentioned estimated values with the actual electrical resistivity of prismatic specimens measured on factory.

Table 4. Estimation of electrical resistivity on prismatic specimens using the 10cm by 20cm cylindrical samples as a reference.

Sample	Curing hours	Type of sample	Elect. Resist. (kohm cm)	Difference
A	15.25	Cyl 10x20	2.45	-
		Prism. 15x15x30 (estimated)	1.73	-1.04%
		Prism. 15x15x30 (actual)	1.75	
B	18	Cyl 10x20	3.10	-
		Prism. 15x15x30 (estimated)	2.19	-0.40%
		Prism. 15x15x30 (actual)	2.20	

From the table, it can be observed that the estimated electrical resistivity values for prismatic specimens differs by less than 1.05% from the actual ones. In conclusion, the calibrations performed in the laboratory for size and shape factors of these types of samples can be applicable to an industrial process.

Moreover, it was observed that resistivity measurements obtained for prismatic samples were lower than the ones obtained for sleepers. While, as mentioned earlier, measurements of the prismatic specimens were taken at a temperature approximately 3-4 °C lower than the temperature at which concrete sleepers were, it would have been expected that the resistivity measured at a higher temperature (sleepers) would be lower than the resistivity measured at a standard temperature (prismatic samples).

The internal increase in temperature due to the heat of hydration of cement may be the cause for this difference. In further works, the direct measurement on the sleepers and the corresponding correction factor will be considered to account for any advantage that the internal heat may provide. At present, it seems that the bigger the dimension of the cross section of the sleepers, the higher the temperature increase.

4.5.2. Correction of results based on measurement temperature

Since the measurements made in the factory on the cylindrical samples were taken at temperatures of 25.6 °C and 25.4°C, for Samples A and B respectively, there would be no need for a temperature adjustment as it falls withing the range of 23 °C ± 3 °C used in the laboratory for calibrating the method. It is important to mention that the specimens were inside the laboratory at the time of measurement due to operational conditions in the factory. To apply the method at industrial scale, especially considering processes with steam curing, resistivity measurements on samples should be taken at the production line and at curing temperature.

4.5.3. Comparison of values obtained in the factory with those obtained in the laboratory

Considering the values of apparent electrical resistivity obtained in the factory on cylindrical samples and the previously defined shape and size factor, the absolute resistivity of the material was calculated. The results of absolute electrical resistivity and compressive strength obtained in the factory are plotted in Figure 9 on the Compressive Strength vs. Electrical Resistivity curve calibrated in the laboratory, previously presented in Figure 6.

From the graph, it can be observed that the values obtained in the factory align satisfactorily with the curve previously calibrated in the laboratory. The very high correlation factors obtained, much higher than the ones obtained by Ali Akbar Ramezanianpour et al (30), can only be reached if the same concrete is under evaluation, as it occurs in a precast plant.

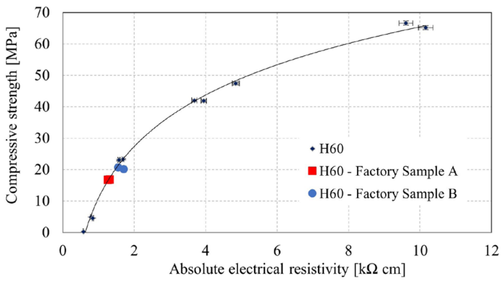

Figure 9. Measurements of Electrical Resistivity and Compressive Strength measured in the factory on the curve calibrated in the laboratory.

4.6. Material and labor hours saving

At first sight, it might be thought that this new methodology may require additional labor hours. However, since resistivity measurements are very quick and the method uses the same samples used at the current quality control process, the adaptation is quite simple. What is more, as was mentioned before, it would be possible to reduce the number of specimens to be molded and the labor hours required in the production process by incorporating electrical resistivity measurements as a predictive method for the early age compressive strength of the specimens to be tested.

Taking a conservative scenario, with a typical Argentinian factory having two production long lines and working two shifts on business days, it is estimated that the monthly savings in sampling would be 352 cylindrical specimens of 10cm by 20cm. Based on productivity data, the reduction of 352 specimens could imply a saving of 88 man-hours per month. These hours consider the time required for moulds' cleaning, concrete filling and compaction, sample demoulding and the development of compressive tests. Additionally, the time saved in monitoring the specimens, disposing of the waste and recording the results should be added to this timeframe.

In terms of material savings, it is estimated that each cylindrical concrete sample weighs around 3.77 kg. Then, with the reduction of 352 cylindrical specimens, a monthly saving of 1327 kg of concrete could be achieved. Beyond the economic benefits, it is essential to highlight the significant environmental benefits associated with this saving. Hammond G. and Jones C, in the Carbon and Energy Inventory (40) have estimated that the embodied carbon of a 40/50 MPa precast concrete for the UK industry is approximately 0.180 kgCO2e/kg of product. In this sense, the 352 specimens would represent a monthly saving of approximately 239 kg CO2e. It is important to mention that this estimation of the kgCO2e/kg of product considers UK recorded plant operation and estimated transportation of the constituents to the factory gate. For more appropriate estimations, the analysis should consider the characteristic of Argentinian industrial sector and the energy matrix.

5. CONCLUSIONS

From the obtained results, it can be concluded that it is possible to calibrate the method as a predictive test for the assessment of early compressive strength of the material at industrial scale.

Firstly, it was verified at the laboratory scale that, for the type of industrially used materials and at an early age of concrete, there is a correlation between the compressive strength and its electrical resistivity, measured by the Wenner method and at laboratory temperature. This relationship follows a logarithmic law with an greater than 0.99. Additionally, it was observed that it is possible to calibrate the influence of the size and shape of the element on the resistivity values obtained on cylindrical samples, which would allow the method to be applied on an industrial scale. Moreover, it has been demonstrated at the laboratory that, for the range of temperatures used in a steam curing process of concrete (25°C to 60°), it is possible to find a correction factor that considers the influence of the testing temperature.

The method was validated in the factory on early-age specimens at ambient temperatures with good correlation. In consequence, it could be concluded that the method showed a high potential for application in the factory, enabling estimation of compressive strength of specimens before testing, thus reducing the number of samples to be tested. The transfer of the results of this study to the production environment could occur through the incorporation of this methodology into regulations as a predictive test for the compressive strength of the samples to be tested. This may increase the reliability and confidence of the product, with a simplification and optimization of the process, and a significantly reduction the number of labor hours required and the generated waste. As any non-destructive test, the elimination of the "inter-sample" variations cannot be overemphasized.

For future studies, it is recommended to assess if a steam curing may lead to a non-saturation condition of elements in the factory, thus affecting the measurement of concrete electrical resistivity. In this line, it would be interesting to validate the curve calibrated in the laboratory for temperature influence under factory conditions. Going forward, if measurements were made directly on a sleeper, the correction factor should be obtained and other considerations besides the one considered in this paper would be required, such as the steel reinforcement location.

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Authorship contribution statement

Melina Scasserra: Data curation; Formal analysis; Investigation; Writing - original draft.

Luis Fernández Luco: Conceptualization; Investigation; Methodology; Project administration; Resources; Supervision; Validation; Writing - review & editing.

Ángel Castillo Talavera: Investigation; Methodology; Project administration; Resources; Supervision; Validation; Writing - review & editing.

Declaration of competing interest

The authors of this article declare that they have no financial, professional or personal conflicts of in-terest that could have inappropriately influenced this work.

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