Investigation of Concrete Moisture Using Non-Destructive Methods Across Different Compositions and Exposure Conditions

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Summary

Studying concrete's interaction with moisture conditions is crucial for understanding material degradation and corrosion of embedded steel reinforcement in structures exposed to atmospheric environments. This work presents a comparative assessment of two non-destructive testing (NDT) techniques for moisture evaluation: internal moisture measurement with the Moist 210 B (HF SENSOR) and electrical resistivity measurement using the Resipod (PROCEQ). Tests involved mass determination for three concrete compositions (with and without a carbonated surface layer) in a climate chamber with ambient relative humidity (RH) levels of 90% and 70%, as well as under saturated and dry conditions. Results showed a strong correlation between the NDT methods and confirmed that concrete composition and carbonation significantly influence material behavior under varying RH conditions.

1 INTRODUCTION

The durability of reinforced concrete exposed to atmospheric conditions is greatly influenced by its moisture content [1]. Atmospheric relative humidity (RH) is commonly used as a proxy for moisture content due to its ease of measurement. This correlation holds under equilibrium conditions, where concrete reaches a stable moisture level within its pores without exposure to wetting cycles [2]. However, in real-world structures, especially in tropical regions, RH can fluctuate significantly, ranging from moderate to high levels (e.g., 70% to 90%), often coupled with intermittent wetting and drying cycles.

Reference [3] showed that the relationship between RH and moisture content in concrete is non-linear, influenced by factors such as the water-cement ratio (w/c) and temperature. Reference [4] showed that under isothermal conditions, where the temperature remains constant, higher RH increases the moisture absorption rate in concrete, with greater absorption capacity at lower temperatures. When RH exceeds 50%, the absorption rate rises significantly. Conversely, lower RH accelerates moisture desorption, and higher temperatures increase the moisture desorption capacity.

The microstructure and porosity of concrete play a critical role in its moisture content and transport rate. These rates tend to increase, particularly when the concrete is modified with supplementary cementitious materials (SCMs), recycled materials, or nanofibers [5]-[8]. Conversely, carbonation reduces porosity and decreases the total pore volume of concrete [9], [10]. When the carbonation front reaches the steel reinforcement, it dissolves the passive layer, exposing the steel to corrosion. The degradation from steel corrosion depends on several factors, with moisture content at the concrete-steel interface (CSI) being crucial in the corrosion rate [11]. Moisture also determines the carbonation rate, as the process is accelerated in partially saturated concrete, which provides voids for CO_2 diffusion while retaining enough water for reactions with alkali ions [1]-[2]-[12].

Porous materials like concrete typically remain unsaturated when exposed to the atmosphere, with moisture transport primarily driven by capillary action. As saturation increases, diffusion—where water moves in response to concentration gradients—becomes the dominant mechanism [13]. During capillary action, water is rapidly absorbed into the concrete, influenced by surface tension, the contact angle between the liquid and pore walls, and the pore radius [2]. Initially, water adsorbs onto the surface of capillary pores. As relative humidity (RH) rises, it condenses, progressively filling the pores from the smallest to the most significant [2], [12].

Laboratory studies underscore the complexities and time-intensive nature of determining concrete's moisture transport properties, with no consensus on the most reliable measurement methods or key parameters [14]. Embedded RH probes, as outlined in ASTM F2170 [15], and non-destructive testing (NDT) methods are widely used in field applications to assess the moisture state of concrete and its associated corrosion risks [16], [17].

NDT techniques are crucial in evaluating concrete durability by examining its microstructure and the transport of water and ions, such as chloride ingress. These processes are directly linked to degradation mechanisms like rebar corrosion. However, accurate interpretation and integration of results from different methods remain challenging, requiring a deeper understanding of factors such as moisture variability, concrete cover thickness, and their combined effects on test outcomes [17].

This article presents the results of a laboratory study evaluating two NDT methods: moisture content measurement using the Moist 210B probe [18] and electrical resistivity with the Resipod probe [19]. While electrical resistivity has been widely studied for assessing durability indicators such as chloride diffusivity and corrosion potential [20], this study explores the combined use of both methods alongside the gravimetric approach. The experiments were conducted on specimens with three different concrete compositions, both with and without a carbonated surface layer, and tested under RH levels of 90% and 70%, as well as in saturated and dry states. It is noteworthy that, in the literature review conducted, no previous studies were found that correlated methods of determining the internal moisture of concrete using non-destructive techniques with the gravimetric method. Consequently, it was not possible to compare the results obtained in this study with data from other authors.

2 MATERIALS AND METHODS

Table 1 summarizes the characteristics of the concrete mixes, which were made with different cement contents (260, 300, and 360 kg/m³) and w/c ratios (0.45, 0.58, and 0.65). The mixes were prepared using CPV ARI Plus Portland cement [21], quartz sand as the fine aggregate, and crushed granite as the coarse aggregate, with a maximum particle size of 12.5 mm. The three concrete types were designed as C260, C300, and C360.

Thirty cylindrical specimens (Ø10 cm x 20 cm) were molded for each type of concrete and cured in a humid chamber for 28 days. Twenty were produced for physical-mechanical evaluation of concrete, and then specimens were produced for internal moisture content study. Subsequently, five (05) specimens of each concrete type were dried for 14 days at 23 °C and 60% RH, followed by exposure to carbonation in a climate chamber at 23 °C, 60% RH, and 3.0% CO_2 [22]. The carbonated samples were designated as ‘C Samples’: C260C, C300C and C360C. The non-carbonated samples (references) were designated as ‘R Samples’: C260R, C300R and C360R. After 18 weeks, the C260C specimens reached a carbonation depth of 10 mm, while the C300C specimens required 24 weeks to reach the same depth. In contrast, the C360C specimens exhibited only 1 mm of carbonation depth even after 36 weeks, which was the depth used for the tests. The higher cement content and lower w/c ratio of the C360 (both C and R) specimens contributed to their superior physical-mechanical performance (Table 1) and slower carbonation rate (C360C). Other five (05) specimens (R Samples) were separated, as well, for internal moisture content study, and these specimens were maintained in a humid chamber during the carbonation process of the ‘C’ samples. The samples destined for the internal moisture content study are shown in Table 1.

Non-destructive techniques for evaluating moisture content (Moist 210B) and electrical resistivity (Resipod) were first applied after saturating ($\boldsymbol{M_s}$, kg) five specimens of each concrete type by immersing them in tap water. After exposing the specimens to a climate chamber, measurements were subsequently taken, first at 90% RH and then at 70% ± 5% RH, both maintained at an ambient temperature of 23 ± 3 °C. Finally, the specimens were assessed after oven-drying at 80 °C for 72 hours. Finally, the specimens were assessed after oven-drying ($\boldsymbol{M_d}$, kg) at 80 °C for 72 hours. Non-destructive tests were conducted only after the specimens’ bulk mass had stabilized (mass variation below 0.5%), allowing for the accurate determination of concrete moisture content (***MC***, %) and degree of saturation (***DS***, %).

The ***MC*** was determined by two different methods: gravimetric and by the use of Moist 210B. The gravimetric method, which is the same applied to soil samples [23] and aggregates for concrete [24], consisted of measuring the specimen's masses along different moist conditions levels and determining its moisture content (***MC***) by the difference between masses on moisture states (100 % RH, 90 % RH, and 70 %) and a dry state. The calculation is described as follows:

$$\boldsymbol{MC} = \frac{m_w - m_d}{m_d \times 100} \quad (1)$$

where $\boldsymbol{m_w}$ is the mass of the specimen under a determined moisture condition (kg) and $\boldsymbol{m_d}$ is the mass of the specimen in a dry state at 80 °C (kg).

The degree of saturation (***DS***, %) is calculated as follows [25]:

$$\boldsymbol{DS} = \frac{m_w - m_d}{m_s - m_d} \quad (2)$$

Table 1 Characteristics of the concrete mixes

Concrete type	Condition	C_C (kg/m³)	w/c ratio	Compressive strength (28 days)	Density (g/cm³)	Capillary water absorption (g/cm²)	Porosity index (%)
C260R	non-carbonated	260	0,65	36,9	2,53	1,03	10,9
C260C	Carbonated (10 mm)						
C300R	non-carbonated	300	0,58	43,8	2,52	0,87	10,4
C300C	Carbonated (10 mm)						
C360R	non-carbonated	360	0,45	55,0	2,54	0,56	8,5
C360C	Carbonated (1 mm)						

The Moist 210B is equipment provided by PROCEQ, which is declared to be able to measure moisture content on different materials by placing its probes' surfaces in contact with the referred materials. The equipment measures dielectric losses from the interaction of the microwave field with water molecules in the porous medium. The moisture content is compared with a reference standard from the manufacturer, enabling the mapping of moisture variations in the structure [16]. Configured for concretes with a compressive strength between 30-37 MPa (2.27 g/cm³), measurements were taken on both transverse faces of the specimens using a probe for readings at a depth of 3 cm (R1M 30920). The superficial electrical resistivity measurements are based on the Wenner method, where the four electrodes of the probe are positioned along the cylindrical specimen's length, starting from the center. Three readings are taken with the Resipod after rotating the specimen by 120°, with a correction factor of 0.377 applied [26]. The Figure 1 shows equipment measurements of concrete internal moisture, with the Moist 210B (left) and concrete resistitivy, with the Resipod (right),

Fig. 1 Measurement of moisture content with Moist 210B (left) and Wenner surface resistivity with Resipod (right).

3 EXPERIMENTAL RESULTS AND ANALYSIS

Fig. 2 presents the average moisture content (***MC***, left) values obtained using the gravimetric method and the corresponding degree of saturation (***DS***, right). As already described, the average moisture content of concrete samples at different environment temperatures and humidity conditions and the 80 °C level was designed as "zero ***MC***," even though it is known that there are still some amounts of water in the concrete microstructure at these conditions.

As shown in Fig. 2, the higher the cement content on concrete, the less water is detected in it. This happens probably because the higher the cement content, theoretically less porous the microstructure is, making the concrete less susceptible to water absorption. This phenomenon happens both in reference samples (C260R, C300R, and C360R) and in carbonated samples (C260C, C300C, and C360C). Analyzing carbonation phenomena on concrete, it is possible to see that carbonated samples have lower ***MC*** values when comparated to reference samples. This happens probably because carbonation promotes concrete superficial pore-clogging, making it less susceptible to water absorption.

Following the drying process, from the 100 % UR state to 90 % UR state, there are no significant alterations in the moisture content of concrete, probably because the difference between these environment humidity states is too small, and the environment humidity is too high at both states, not allowing concrete saturation to be altered by it.

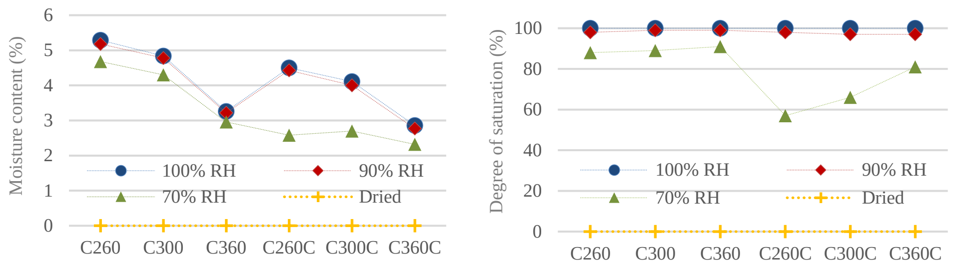

Fig. 2 Moisture content (***MC***, %) results obtained by the gravimetric method (left) and degree of saturation (***DS***, %) (right).

Fig. 3 presents the average moisture content (***MC***, left) values obtained using the Moist 210B probe and the average surface resistivity values (right) measured with the Resipod. It is observed that residual ***MC*** readings were possible for the concretes in the dry condition, whereas no surface resistivity measurements could be obtained under the same condition. This ***MC*** (Fig. 3, left) result indicates that the assumption of zero moisture content in the gravimetric test (Fig. 2) under dry conditions carries some uncertainty. Nevertheless, the ***MC*** results clearly distinguish the dry condition from the others. A slight differentiation was observed for the carbonated concretes, with values slightly lower at 70% RH, particularly for C260C and C300C. This differentiation was more clearly represented by the surface resistivity measurements, where C260C exhibited the highest value, followed by C300C and C360C. Similar to the MC measurements, surface resistivity did not distinguish between the concretes at 100% and 90% RH, as observed in the gravimetric method (Fig. 2).

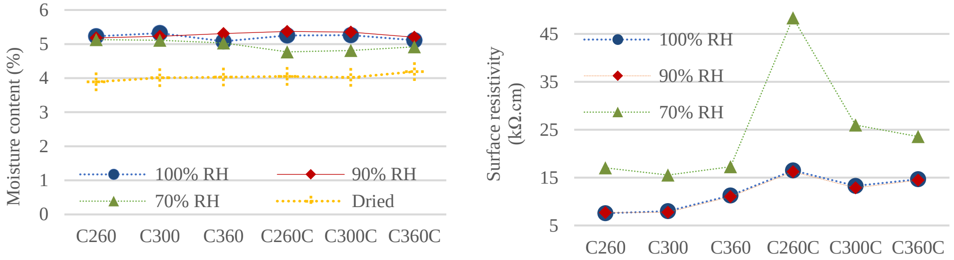

Fig. 3 Moisture content (***MC***, %) was measured using the Moist 210B (left), and surface resistivity (kΩ.cm) was measured using the Resipod (right).

The correlation between the gravimetric method for determining the ***MS*** content and the Moist 210B method was analyzed. This analysis was conducted in two different ways: the Pearson correlation coefficient (R) and the variance analysis (ANOVA) with a 95 % confidence level. The results of both methods are shown in Table 2, as well as the results of Pearson's correlation between them. The ANOVA is shown in Fig. 4.

Even though one can see the Pearson correlation coefficient results in Table 2 and establish that the use of Moist 210B is highly correlatable to the gravimetric method, the ANOVA was used as a resource to refine and increase the level of confidence in this analysis. Both methods (Pearson and ANOVA) reveal, this way, that the use of Moist 210B is correlatable to the gravimetric method until a certain point, with some conditions established, such as the environment humidity and temperatures on which this study was conducted.

Table 2 Correlation and results of gravimetric and Moist 210 B methods.

Sample	***S* content on each UR condition**								**Pearson correlation coefficient (*P*)**
	Gravimetric method				**Moist 210B method**				
	100 % UR	90 % UR	70 % UR	After drying	100 % UR	90 % UR	70 % UR	After drying	
C260R	5,24	5,23	4,73	0,0	5,23	5,18	5,13	3,89	0,9988
C300R	4,80	4,80	4,31		5,32	5,23	5,11	4,01	0,9974
C360R	3,24	3,24	2,98		5,08	5,31	5,03	4,03	0,9844
C260C	4,49	4,44	2,58		5,25	5,37	4,77	4,05	0,9958
C300C	4,06	4,03	2,72		5,26	5,35	4,81	4,02	0,9959
C360C	2,85	2,80	2,34		5,11	5,20	4,92	4,19	0,9927

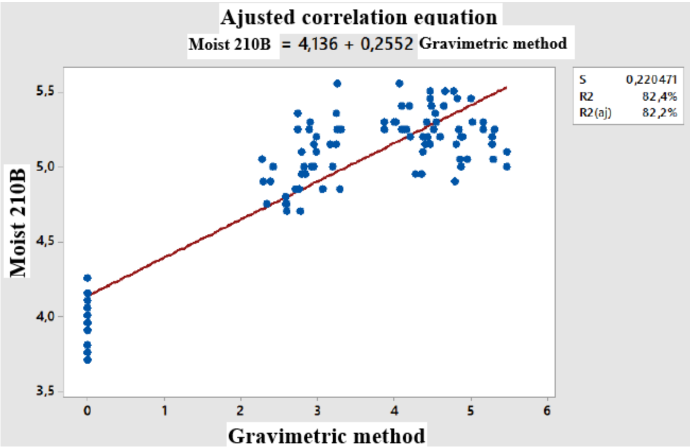

Fig. 3 Ajusted line graphic created with regression analysis between results obtained with Moist 210B and gravimetric methods.

4 CONCLUSIONS

Reviewing the main objective of this work, which was to verify and analyze the correlation between the Moist 210B and the gravimetric method to determine concrete internal moisture content, it is possible to say that, considering the current statistic methods adopted, there is a significant correlation between the equipment (Moist 210B) and the gravimetric method. This sets a precedent for its future use as a mechanism to evaluate moisture on concrete structures.

However, it has to be considered that the conditions established for performing this study were determinants of the results. Such conditions include cement content used (260, 300, and 360 kg/m³), w/c ratios, carbonation depths of concrete specimens, and different environmental temperature and humidity conditions. The results obtained for the samples produced this way cannot necessarily be replicated to concretes produced or submitted to different conditions, such as the concrete structures on the field.

Even so, it is essential to expand the Moist 210B studies, focusing on different cement types and contents, variations on the w/c ratio, as well the environmental conditions that concrete will be exposed to, to create a solid database that will allow to confidently correlate the results obtained with the equipment to the analysis made in laboratory conditions.

In general, water remains a key agent in most concrete degradation processes, and its content on concrete may be an essential factor in enabling new diagnostics and identifying prematurely harmful phenomena in concrete structures. Thus, concrete internal moisture is an essential factor to non-destructive analysis, and techniques to evaluate it (such as equipments as Moist 210B) are important resources to concrete structures diagnostics.

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