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Moisture in Concrete Aggregates and its relation to the Dielectric Constant

Humedad y su relación con la espectroscopía dieléctrica en agregados de concreto

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Abstract

Measurement of moisture content (CH) of concrete aggregates (AOC) in the manufactury of ready mixed concrete is one of the currently challenges in the building industry since affect to the final properties of concret. At present, the methods for measurement of CH in AOC are invasive and destructive. This paper presents a novel sensing technique using dielectric espectroscopy (ED), a method that using the propagation of microwaves on the material allows the correlation of its dielectric constant (CD) and its CH. In this research is used this method in AOC. Three diferents peruvian quarries (Moyobamba, Sol sol y Cerro Mocho) have been used. The results shows that the sensor at the frequency of 1.5GHz is capable of detecting the CH in AOC with linear regression of $R^2 = 95\%$. In conclusion, is available using the ED as a online and no invasive sensing method of CH in AOC for using in the building industry.

Keywords: moisture contentent, microwaves, dielectric spectroscopy, dielectric contant, concrete aggregates.

Resumen

Medir el contenido de humedad (CH) de los agregados de concreto (ADC) en la fabricación de concreto premezclado es uno de los retos actuales en la industria de la construcción porque afecta a las propiedades finales del concreto. Actualmente los métodos que se utilizan para medir el CH en ADC son invasivos y destructivos. Este artículo presenta una técnica moderna basada en espectroscopía dieléctrica (ED), un método que al propagar microondas en el material correlaciona su constante dieléctrica (CD) y su CH. En esta investigación se ha utilizado este método en ADC. Tres diferentes canteras peruanas de ADC (Moyobamba, Sol-Sol y Cerro Mocho) han sido utilizadas. Los resultados demuestran que el sensor a una frecuencia de 1.5 GHz es capaz de detectar el CH en ADC con una regresión lineal de $R^2 = 95\ \%$. En conclusión, se puede utilizar la ED como un método de sensado no invasivo y en línea de CH en ADC para ser utilizado en la industria de la construcción.

Palabras clave: contenido de humedad, microondas, espectroscopía dieléctrica, constante dieléctrica, agregados de concreto

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1. Introduction

The moisture content (MC) of a material is a parameter that many industrial sectors seek to control in their processes, because it impacts the final characteristics of the product. In the construction industry, the MC of the concrete is important since it defines the mechanical properties and the useful life of a civil project [1]. Studies have been carried out to analyze the durability and resistance in concrete structures measuring the MC [2], and also in concrete test tubes [3]. No research studies have been conducted about systems for measuring the MC of the AOC online, during the mixing process in the plant. Authors in [4–6] show different techniques to perform the measurement of the MC of materials. In the present paper it is utilized a methodology based on dielectric spectroscopy, which has been tested in soil [7], wool [8], paper [9], fabric [10], flour [11], wood [12–14].

There are various methods for measuring the MC of materials, which are classified in direct and indirect. In the direct methods the MC is obtained without correlating with other variables. These are the thermogravimetric and chemical methods. The thermogravimetric method is not selective [15, 16], the effective measuring range varies from 0.5 % to 99.9 % for the MC, and its precision is 0.5 % of the total mass. In contrast, the chemical method [17–19] is selective, it has a precision of 0.0001 % and a measuring range from 0.00001 to 99.9 % of MC.

The indirect methods require a prior calibration to obtain the MC using direct methods. The indirect methods are classified in passive and active. The former utilize elements such as variable resistances or capacitances to determine the MC, which is by nature an invasive control. The active are those that emit electromagnetic waves to determine the characteristics of the medium, thus guaranteeing and online control and the integrity of the sample by not being invasive nor destructive.

The results of different research works in [20–23] in the field of active methods, demonstrate that there is a relationship between the MC and the relative permittivity (ε') or dielectric constant (DC) [24] of a material.

The indirect methods use techniques such as the DS, which seeks to measure the DC of the material, and is also utilized for other purposes such as characterizing materials. Another indirect technique is the use of hyperspectral images, which has had good success in bioengineering [25] and in agroindustry [26–29].

Authors show applications with DS oriented to the agriculture, with the purpose of estimating the quality of their products [30–41], which include applications in seeds, wheat, grains, nuts, fruits of oil palm and bananas.

This paper describes theoretical concepts of the DS and its relationship with the MC [6]. An application is presented that uses the DS to seek for the correlation between the MC and the DC of AOC with different quarries, and verifying the possibility of this new method in this industry.

1.1. Description of the electromagnetic waves

Electromagnetic fields refers to the group of fields of electric and magnetic forces produced by electric charges and currents in movement through the vacuum or any type of matter. When an electromagnetic field propagates in the space it is called propagation of electromagnetic waves.

The propagation of electromagnetic waves is based on the solution of Maxwell's equations.

$$\nabla \times \overline{E} = \overline{M} - \frac{\partial \overline{B}}{\partial t} \; (Faraday's\ law) \tag{1}$$

$$\nabla \times \overline{H} = \overline{J} - \frac{\partial \overline{D}}{\partial t} \; (Ampere's\ law) \tag{2}$$

$$V.\overline{D} = \rho \; (Gauss's\ law) \tag{3}$$

$$V.\overline{H} = 0 \; (Gauss's\ law) \tag{4}$$

Where:

E is the electric field [V/m]
H the magnetic field [A/m]
M is the density of magnetic current [V/m^2]
J is the density of electric current [A/m^2]
B is the density of magnetic flux [Wb/m^2]
D is the density of electric flux [Coul/m^2]
ρ is the density of charge [Coul/m^3]

In order to solve Maxwell's equations it is supposed propagation in free space and, besides, a sinusoidal and harmonic time-dependent field that propagates in the z-axis and is polarized in the x-axis.

By using these assumptions and combining the given equations, it is generated the second orden equation, known as homogeneous Helmholtz vector equation for E.

$$\nabla^2 E + k^2 E = 0 \tag{5}$$

where k is the wave number, which for a lossless medium is expressed as:

$$k = \omega\sqrt{\varepsilon_0 \mu_0} = \frac{\omega}{c_0} = \frac{2\pi}{\lambda}\left(\frac{rad}{min}\right) \tag{6}$$

where:

ω is the angular frequency of propagation
ε_0 is the vacuum permittivity
μ_0 is the vacuum permability

Solving (5) yields:

$$\overline{E}(z,t) = \overline{a_x}\varepsilon_0 cos(\omega t - kz) \tag{7}$$

which takes the phasor value:

$$\overline{\varepsilon}(z) = \overline{a_x}\varepsilon_0 e^{-jkz} \tag{8}$$

The following expression can be used to give the phasor vector in sinusoidal form:

$$\overline{E}(z,t) = Re\{\overline{\varepsilon}(z)e^{j\omega t}\} \tag{9}$$

Figure 1 shows the propagation of the electric field in free space, where the given hypotheses have been been taken into account.

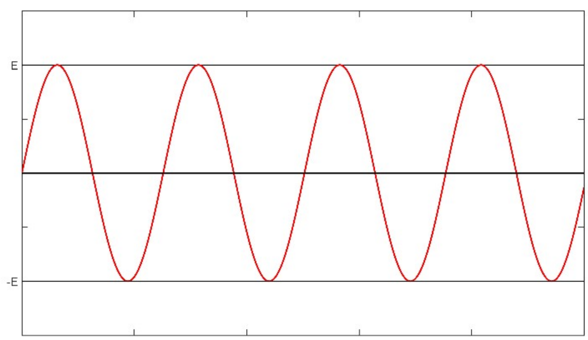

Figure 1. Representation of an electromagnetic wave that travels in free space [11].

1.2. Propagation of the waves in a medium with losses

The hypotheses defined in the preceding sub-section consider the propagation of electromagnetic waves in the vacuum. These are now extended to materials with losses, i.e., conventional materials.

According to their behavior in front of fields, the materials are classified in good conductors, when they allow electric fields pass through them, or as dielectrics, when they store electric energy inside and form polar molecular bonds that are known as electric dipoles. In general, a material has a conducting part and a dielectric part. Their behavior is determined by means of the complex permittivity of the material, which is defined as:

$$\varepsilon_c = \varepsilon' - j\varepsilon'' \tag{10}$$

Where ε' is the dielectric constant of the material, that measures the amount of formed dipolar moments and represents the energy stored in the material, and ε'' is the constant of losses that represents the energy that is not stored in the material, but that is somehow propagated or reflected, which is represented as:

$$\varepsilon'' = \varepsilon''_r + \frac{\sigma}{\omega} \tag{11}$$

Where σ is the conductivity of the material such that:

$$\overline{J} = \sigma\overline{E} \tag{12}$$

It is obtained an equivalent conductivity that represents all the losses in the medium.

$$\sigma_{eq} = \omega\varepsilon'' \tag{13}$$

The «tangent of losses» is a measure of the power losses in the medium, and is defined as.

$$tan\ \delta = \frac{\varepsilon''}{\varepsilon'} = \frac{\omega\varepsilon'' + \sigma}{\omega\varepsilon'} \tag{14}$$

Therefore, the solution of Maxwell's equations through the homogeneous Helmholtz vector equation for E takes the form:

$$\nabla^2\overrightarrow{E} + k_c^2\overrightarrow{E} = 0 \tag{15}$$

$$k_c = \omega\sqrt{\varepsilon_c\mu}(m^{-1}) \tag{16}$$

where k_c is the complex wave number, i.e., that takes the complex value of the permittivity of the medium, which behaves in phasor mode when taking a sinusoidal electric field. Besides, the vacuum permittivity is expressed as a real value, since it will have no losses:

$$\varepsilon_0 = 8.854 \times 10^{-12}\frac{F}{m}$$

Therefore, this form of behavior of the materials makes the electromagnetic waves to attenuate at the moment of hitting them; part of the energy will be stored in the polar bonds and part will leave as energy losses. As a result, the concept of propagation constant is defined as:

$$y = \alpha + j\beta = j\omega\sqrt{\mu\varepsilon'}\left(1 + \frac{\sigma}{j\omega\varepsilon}\right)^{\frac{1}{2}} \tag{17}$$

Using the definition of tangential loss:

$$y = \alpha + j\beta = j\omega\sqrt{\mu\varepsilon'}\left(1 - j\frac{\varepsilon''}{\varepsilon'}\right)^{\frac{1}{2}} \tag{18}$$

Where α is the constant of attenuation and β is the constant of phase.

Then, the primary solution given in vacuum is written as:

$$\overline{E}(z,t) = \overline{a_x}\varepsilon_0 cos(\omega t - \beta z) \tag{19}$$

which takes the phasor value:

$$\overline{\varepsilon}(z) = \overline{a_x}\varepsilon_0 e^{-j\beta z} \tag{20}$$

where:

$$\overline{E}(z,t) = Re\{\overline{\varepsilon}(z)e^{j\omega t}\} \quad (21)$$

Figure 2 shows the representation of this attenuation of an electric field that hits a material with losses.

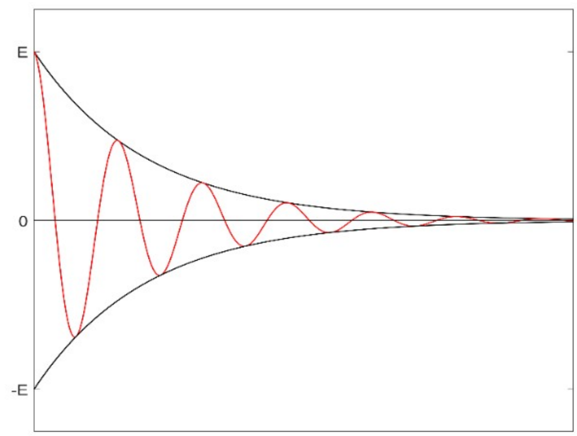

Figure 2. Representation of an electric field that travels in a medium with losses [11].

The energy lost at the moment of the propagation on the material is called this way, because it is stored in the material forming polar bonds; part of this energy is reflected from the material and part goes through it, according to the value of its conductivity. This is seen in Figure 3. It is observed an incident electric field (in green) that collides in the medium (blue lines), and part of it is reflected (in red) and part is propagated by the field (in orange).

All this is quatified in the complex permittivity.

In all this analysis it is assumed that the material is isotropic, i.e., that the dipolar moments or that the polar bonds occur in the direction of the electric field; this does not occur in anisotropic materials, but this analysis is not taken into account in this research, because isotropic AOC have been considered.

The reflected part of the field can be related with respect to the incident field by means of the reflection coefficient Γ, which relates the reflected wave and the incident wave of the field

$$\Gamma = \frac{E_r}{E_i} \quad (22)$$

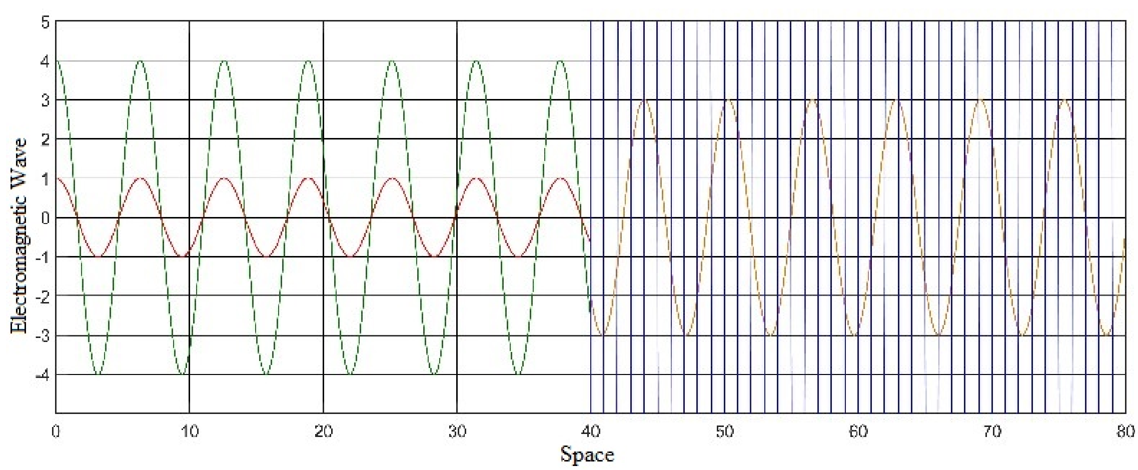

Figure 3. Behavior of the propagation of an electromagnetic wave in front of a change of medium [11].

Replacing the equation of the wave to express it in terms of the electric field, yields:

$$E_r(z) = \Gamma E_0 e^{y_1 z}\alpha_x \quad (23)$$

The equation of the magnetic field of the propagated and reflected wave is directed in the direction orthogonal to the electric field:

$$H_r(z) = \Gamma \frac{E_0}{n_1} e^{y_1 z}(-a_y) \quad (24)$$

It is possible to measure the electric field that hits a material, the propagated field and the reflected field, in accordance with the equations given in the theory. With all this it can be assumed that it is possible to deduce the values of DC that will take the material when analyzing the relationship between these quantities.

1.3. Dielectric properties of the molecule of water

The water is a dielectric, i.e., it contains in its structure polar molecules that form dipolar moments when being in contact with an electric field, and thus a greater amount of water will result in a greater measured DC.

A dry material will have a behavior established according to its molecular structure, and will be normally homogeneous if this structure remains unalterable when subject to a temperature increase or when mixed with water. The AOC, due to their shape and properties, have a homogeneous structure. Therefore, their dielectric constant will remain unalterable when moistened. However, a higher moisture will increase the dipolar moment of the mixture due to the water present, which will produce a change in the DC of such mixture due to the increase in water. Therefore, the DC of the mixture will be related with the MC of the AOC, and if the MC and the DC of the mixture can be measured, it will be possible to determine a correlation between them for future prediction and use as a sensing system.

2. Methodology

It was seen in the previous section that it is possible to correlate the value of the MC of the AOC with the DC of the mixture, because the quantity of dipolar moments will increase according to its MC. In addition, it has been theoretically seen that it is possible to determine the DC of the mixture using Maxwell's equations and their solution for media with losses. This section presents the experimental methodology which was followed to determine such correlation.

It should be noted that the field emmited is the field that collides with the material, and the propagated field is the one that goes through the material.

2.1. Materials

The DC uses frequencies in the microwave range for the propagation of the electromagnetic fields; therefore, two aperture antennas are utilized to emit and receive the incident and propagated fields, respectively (see Figure 4).

Figure 4. Aperture antennas utilized in MC measuring tests.

A system for analyzing vector signals has been also utilized to emit the electromagnetic field, as it is seen in Figure 5. The phase and amplitude variation of the signal is analyzed, to further determine the DC.

Figure 5. Wavetester equipment for analyzing vector signals.

The analyzer of vector signals utilizes a software for data detection.

A sensing platform has been also constructed to carry out the experimentation, on which the AOC has been placed to measure its DC and its MC. Other utilized materials include: scales, measuring containers, drying oven, etc.

The sample is placed between the receiver and trasnmitting antennas, where it is measured the effect on the AOC of the wave propagating in free space between the two antennas.

2.2. Experimentation

Three Peruvian quarries of AOC have been utilized to perform the calibration of the system: Cerro Mocho, Moyobamba and Sol-Sol. To determine the correlation between MC and DC it has been proceeded the following way:

An initial mass (m_0) has been defined as the total mass of AOC provided by the quarry. Then a thermogravimetric drying has been carried out to obtain the value of dry mass (m_s), i.e., without MC. This value of m_s has been divided into 4, and each of theses samples has been named sampling dry mass and have been numbered from 1 to 4 (m_{smx}), where the subscript x corresponds to the number of the subsample. Then the sample m_{sm1} is selected and placed on the sensing platform, the electromagnetic field is emitted on the material, and with the help of the signal analyzer the value of the DC for m_{sm1} is measured. This value of DC corresponds to the value of 0 % of MC. The mass of water (m_{H_2O}) corresponding to 0.5 % m_{sm1} is added to m_{sm1}, and the same procedure is carried out for measuring its DC. Then 0.5 % m_{sm1} is added again and the DC is measured, which corresponds to 1 % of its MC. This procedure is repeated until reaching 10 % of MC

$$m_{h2O} = 0.005 \times m_{sm1} \tag{25}$$

It should be clarified that the following relationships are met in the experimentation:

$$m_{sm1} = m_{sm2} = m_{sm3} = m_{sm4} \tag{26}$$

$$m_{sm1} + m_{sm2} + m_{sm3} + m_{sm4} = m_s \tag{27}$$

The distance between antennas was 23 cm, the thickness of the sample was established in 40 mm, and the frequency of emission of the electromagnetic field was 1.5 GHz.

m_{sm1} and m_{sm2} were utilized to make the curves of correlation, and m_{sm3} and m_{sm4} to validate the results. It should be remarked that, at all times, the DC of the mixture of the moistened AOC is measured.

3. Results

With the values of DC *vs.* MC obtained for each quarry, the calibration curve is fitted by means of linear regression models. In this fit the MC is set as the dependent variable, and the DC as the independent variable with different effects: linear, quadratic, cubic and of fourth order.

The «Stepwise Forward» method was applied for selecting the linear regressiong model, to determine which of the effects of the DC better fits with the MC. This classical method for the selection of variables initiates with an empty model, and in each iteration evaluates incorporating some of the defined effects of the dielectric constant: linear, quadratic, cubic and of fourth order. It is decided to incorporate some of the aforementioned effects if it meets the defined significance level: P Value smaller than 0.05. The «Stepwise Forward» method finalizes when no more effects can be incorporated, because they do not meet the significance level. In order to evaluate the level of significance of the effects, a hypothesis test with «T-Student» is carried out. In this test it is verified if the estimated coefficient of the effect is equal or different than zero.

$$H_0 : b_i = 0 \tag{28}$$

$$H_1 : b_i \neq 0 \tag{29}$$

If the null hypothesis is rejected ($b_i \neq 0$), the effect is significant.

In hypothesis contrasting, it is calculated the relationship between the estimated coefficient of the effect (b_i) and its standard deviation (S_{b_i}), and it is compared with the critical t for a confidence level of 95 % ($\alpha = 0,05$).

$$\frac{b_i}{S_{bi}} > j_{N-1}^{\alpha/2} \tag{30}$$

If the relationship is met, the null hypothesis is rejected. In this condition it is met that the «P value» is smaller than 0.05.

In fitting the regression model it was also found necessary to apply the Cochrane-Orcutt iterative procedure, to correct the autocorrelation present in the data. This autocorrelation is the result of sequentially adding the variation of the moisture, and with this correction the estimation of the parameters is improved.

The results of the tests are presented in the following.

3.1. Cerro Mocho quarry

The model was selected by means of «Stepwise Forward», where it is obtained

$$(CH\ \%) = -7.372 + 3.206 \times CD \tag{31}$$

In this model, the linear effect of the dielectric coefficient with respect to the expected value of moisture results significant. Table 1 shows the results of the hypothesis contrasting, where the «P value» of the linear effect is smaller than 0.05. It was obtained a linear regression model of $R^2 = 95.8057$ % and a standard error of 0.382134.

Table 1. Significance of the effect of the variables

Parameter	Estimated value	Standard error	T-Student	P Value
Constant	7.37238	0.378829	19.461	0.000
Dielectric_const	3.2059	0.0740563	43.29	0.000

Figure 6 shows the relationship between the dielectric constant and the moisture; Figure 7 shows the relationship between real and predicted values of moisture.

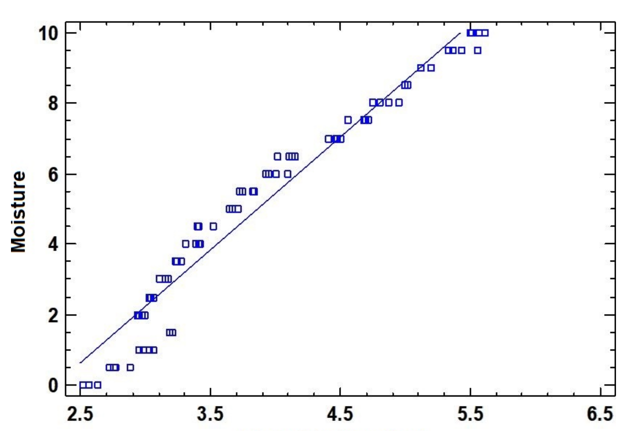

Figure 6. Plot of the fitted model.

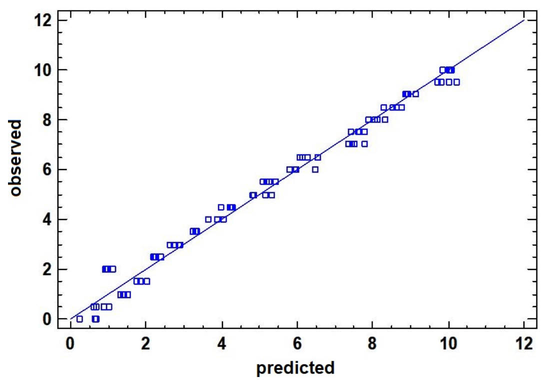

Figure 7. Graphical relationship between observed and predicted values of moisture.

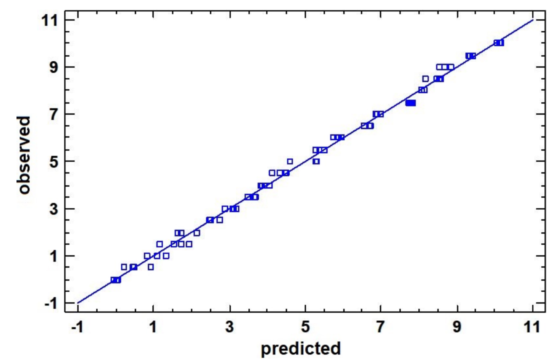

Figure 9. Graphical relationship between observed and predicted values of moisture.

3.2. Moyobamba quarry

The model was selected by means of «Stepwise Forward», where the linear, quadratic and cubic effects of the dielectric constant with respect to the expected value of moisture are significant

$$(CH\,\%) = 38.55{+}18.15{\times}CD{-}2.52{\times}CD^2{+}0.13{\times}CD^3$$

Table 2 shows the results of the hypothesis contrasting, where the «P value» of the effects is smaller than 0.05.

Table 2. Significance of the effect of the variables

Parameter	Estimated value	Standard error	T-Student	P Value
Constant	38.55	1.93216	19.9518	0.000
Dielectric_const	18.1473	1.045	17.3657	0.000
Dielectric_const2	2.52011	0.18239	13.8172	0.000
Dielectric_const3	0.1253	0.0102973	12.1681	0.000

It was obtained a linear regression model of $R^2 = 99.5097\ \%$ and a standard error of 0.201714.

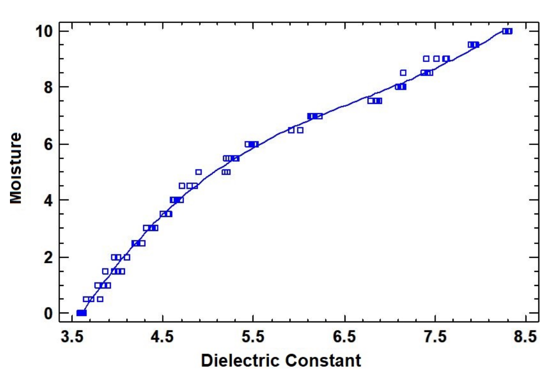

Figure 8. Plot of the fitted model.

Figure 8 shows the relationship between the dielectric constant and the moisture; Figure 9 indicates the relationship between real and predicted values of moisture.

3.3. Sol-Sol quarry

The model was selected by means of «Stepwise Forward».

$$(CH\ \%) = -15.5262 + 7.26581 \times CD - 0.506717 \times CD^2 \quad (32)$$

Where the linear and quadratic effects of the dielectric constant with respect to the value of moisture resulted significant. Table 3 shows that the «P value» of the effects is smaller than 0.05.

Table 3. Significance of the effect of the variables

Parameter	Estimated value	Standard error	T-Student	Valor P
Constant	-15.5262	0.875589	17.7323	0.000
Dielectric_const	7.26581	0.41318	17.5869	0.000
Dielectric_const2	0.506717	0.0477948	10.6011	0.000

It was obtained a linear regression model of $R^2 = 97.1325\ \%$ and a standard error of 0.297068.

Figure 10 shows the relationship between the dielectric constant and the moisture, while Figure 11 shows the relationship between real and predicted values of moisture.

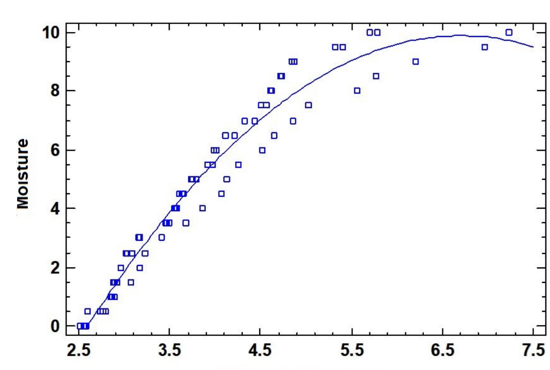

Figure 10. Plot of the fitted model.

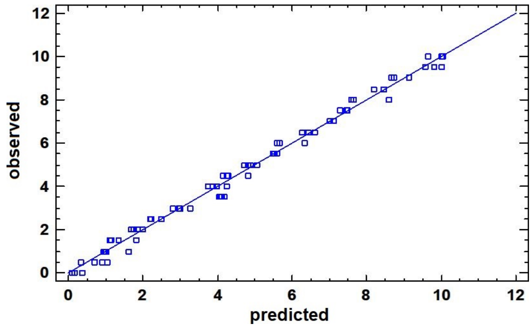

Figure 11. Graphical relationship between observed and predicted values of moisture.

4. Discussion of results

From the results obtained in the previous section, it is interesting to see that in the frequency of 1.5 GHz, the linear regression correlations maintain an R^2>95 %, as seen in Table 4.

Table 4. Comparison of results

Cantera	R^2	Error estándar
Cerro Mocho	95.8057	0.382134
Moyobamba	99.5097	0.201714
Sol-Sol	97.1325	0.297068

It can be also seen that there is a direct relationship between the MC and the DC, i.e., a greater MC results in a larger value of DC.

Comparing the equations for predicting the MC, it can be observed that, depending on the origin of the AOC, it is defined its calibration curve, which can vary between linear, quadratic or cubic; hence, for practical purposes, the AOC should be first calibrated according to a specific quarry before carrying out the measurement and this curve cannot be used for another quarry, since the values of DC differ between quarries. This was expected because the DC depends on the molecular properties and on the energy storage capacity, which means that each AOC has a different structure at a molecular level.

5. Conclusions

The measurement of MC with devices that utilize microwaves has advantages over invasive methods, because they do not damage the material. The measurement of the DC with this methodology analyzes internally the behavior of the material to define its DC, since it studies the dipolar moments formed when electromagnetic fields are induced in the material. It can be used in the presence of vapors or in dirty environments, while the AOC is not molecularly changed, since these do not interfere with the microwave signals. Therefore, the DS enables the measurement of a broad range of materials, whether they are solids, gases or liquids.

The measurement is carried out without contact with the material. The method is not invasive nor destructive. The meaurement is carried out in real time and online with the process.

It is interesting to observe the relationship found by different authors. In [17] the author defines a linear or polynomial relationship. The parameters that influence the calculation of the dielectric constant, and the relationship between the moisture content and the temperature are shown.

It has been verified that with the methodology based in DS at 1.5 GHz, linear correlation values of high precision (R^2>95 %) are obtained for each of the quarries. The system has been validated in a horizontal conveyor with fine aggregate and antennas arranged vertically.

The results obtained show the relationship between the MC and the DC in AOC, and it has been observed a variation in the calibration curve between different quarries.

This sensing system exhibits a high potential to be used for measuring the MC in AOC, in the process of concrete production.

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