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DESENVOLVIMENTO DE SENSOR DE UMIDADE DO SOLO UTILIZANDO O PRINCÍPIO DA RESISTÊNCIA ELÉTRICA

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1 RESUMO

A determinação do teor de água do solo é usada para decisões de manejo de irrigação. Com isso, objetivou-se avaliar tipos de eletrodos e materiais de enchimento e encapsulamento no desempenho de sensores de umidade do solo. Com base no princípio da resistência elétrica, diferentes sensores foram confeccionados e avaliados em um delineamento de blocos casualizados em esquema fatorial de 2 x 5, com dois eletrodos (20 x 5 e 15 x 5 mm) e cinco materiais de enchimento e encapsulamento (areia grossa + gesso com 30% pó de mármore, areia fina + gesso com 30% pó de mármore, lã de vidro + gesso com 30% pó de mármore, areia fina + gesso com 30% areia fina e areia grossa + gesso com 30% areia fina), com quatro repetições. Os resultados indicaram que os eletrodos de anéis concêntricos de tela de inox fixados com resina de poliéster mantêm uniforme as leituras de condutividade elétrica na medição da tensão da água no solo. Os eletrodos de 20 x 5 preenchidos com areia fina e encapsulado com gesso + pó de mármore foram mais sensíveis às baixas tensões e com leituras mais precisas da umidade do solo.

Palavras-chave: agricultura de precisão, eficiência do uso da água, manejo da irrigação.

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DEVELOPMENT OF SOIL MOISTURE SENSOR USING THE PRINCIPLE OF ELECTRIC RESISTANCE

2 ABSTRACT

The determination of soil water content is used for irrigation planning decisions. This study aimed to evaluate electrode types and filling and encapsulation materials on the performance of soil moisture sensors. Based on the principle of electric resistance, different sensors were made and evaluated in a randomized block design in a 2 x 5 factorial scheme with two electrodes (20 x 5 and 15 x 5 mm) and five filling and encapsulation materials (coarse sand + gypsum with

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30% marble powder, 30% fine sand + 30% marble sand, 30% sand and gypsum with 30% sand) with four replicates. The results indicated that the concentric stainless steel mesh ring electrodes fixed with polyester resin keep the electrical conductivity readings uniform in the measurement of soil water tension. The 20 x 5 electrode filled with fine sand and encapsulated with gypsum + marble powder were more sensitive to low voltages and with more accurate readings of soil moisture.

Keywords: precision agriculture, water use efficiency, irrigation management.

3 INTRODUCTION

Although irrigation is considered one of the alternatives for the socioeconomic development of arid and semiarid regions, it is limited by low water availability. Considering that irrigated agriculture requires a large volume of good-quality water, approximately 70% of that used by humans, water management and efficiency become essential for sustainable cultivation (ROST et al., 2008). To increase water use efficiency, it is essential to plan irrigation—that is, to know how much and when to irrigate to avoid water loss and improve crop yields (LIMA, 2009). The soil water content is the main element used for decision-making in irrigation planning and is widely used in irrigation water management in agriculture (CÁRDENAS-LAILHACAR; DUKES; MILLER, 2010; CÁRDENAS-LAILHACAR; DUKES, 2012, 2014).

There are several methods for estimating the amount of available soil water and calculating the daily water requirements of plants. Some methods are based on estimating crop evapotranspiration, whereas others measure variations in the soil water status. Electrical resistance (Boyucus), tensiometry, neutron moderation, and time-domain reflectometry (TDR) methods are used to measure variations in soil water status (SOUZA et al., 2016). Currently, several commercial electrical resistance sensor models are available for determining soil moisture and monitoring irrigation. These sensors offer the advantages of low cost, the ability to operate over a wide range of soil moisture levels, easy automation of data collection, and a lack of adjustment after installation. However, acquiring reading equipment and sensors on the Brazilian market is a difficult task, and in most cases, these products do not have a long useful life, presenting good accuracy only for higher voltages (30 to 500 kPa) and consequently having low efficiency for use in localized irrigation that normally operates at voltages lower than 30 kPa.

Thus, the aim of this study was to evaluate the effects of the type of electrode and filling and encapsulation materials on the performance of soil moisture sensors.

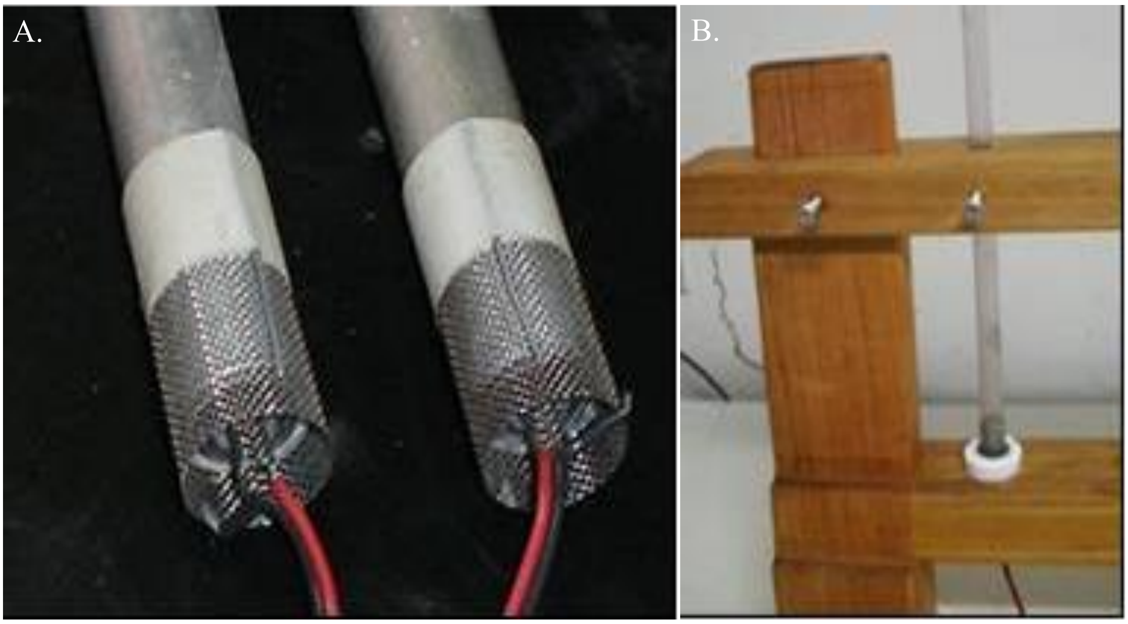
4 MATERIALS AND METHODS

A reliability and accuracy study of the resistance sensors was carried out at the Irrigation and Drainage Laboratory of the Federal Rural University of Semi-Arid (UFERSA).

The sensors were made from 30-mesh stainless steel screens cut to 23 mm in height and formed cylinders with four diameters (5, 10, 15, and 20 mm), forming the sensor electrodes. To make the ring, electronic welding was used to join the two ends of the rectangular screen and to connect the wire to the rings. The wire used was 2 × 0.5 mm² and was 1 m long for each sensor with a two-tone coating, with one wire connected to each ring.

Polyester resin was used to fabricate the sensor base, leaving the rings (electrodes) concentric and with a height (outer part) of 19 mm, with the remaining 4 mm fixed to the resin. The connection between the wire and the mesh rings was placed inside the resin to make the external area uniform and provide greater safety in handling. During the electrode assembly process, molds were used to support the rings, and a wooden structure served as a support for applying the resin. The molds consisted of two concentric pipes (one inside the other) used to adjust the electrodes in the center of the resin base (Figure 1A).

Figure 1. (A) Electrode molds and (B) structure for resin application.



sensor base was constructed of plaster with an opening matching the dimensions of the desired resin base. This mold was made using a rod of the desired diameter and disposable cups as a mold to facilitate the precise construction of the sensor. In this mold, the resin was dried, the electrodes were attached, and the mold had diameters equal to those of the sensor's external encapsulation mold. Because it is a porous material, plaster was used as a waterproofing agent to prevent resin penetration into the pores and facilitate mold removal. Demolding was accomplished by destroying the plaster mold.

The electrodes were constructed in two configurations: 20 × 5 mm and 15 × 5 mm (Figure 2). The electrodes were subsequently identified, and the cell constant was determined by measuring the electrical conductivity (EC) via a benchtop conductivity meter (measurement range between 20 and 2000 dS m $^{-1}$, with 1% FS accuracy and without temperature compensation).

Figure 2. Electrodes constructed with stainless steel screen molds with (A) 20 × 5 mm, (B) 15 × 5 mm and (C) encapsulated sensors.

To measure these constants, four saline solutions with electrical conductivities of 1.41, 4.73, 9.20, and 11.91 dS m $^{-1 \text{ were used}}$, and these values were used to correlate the electrical conductivity readings obtained from the sensors with the actual electrical conductivity readings of the four saline solutions.

In the encapsulation process, for different internal and external materials, the internal material was initially placed between the electrodes, and then the pore space of the material was filled with a saturated gypsum solution (CE = 2.20 dS m $^{-1}$) to facilitate equilibrium between the internal CE and the CE of the coating material. For similar internal and external materials, gypsum powder was mixed, a saturated paste was prepared, and it was applied simultaneously to fill the electrodes and encapsulate them.

For internal and external coatings with the same material or complete coatings with the same material, plaster was mixed with 30% inert material, i.e., sand or marble dust, to increase the porosity and improve the low-voltage response. The water volume added was the same as the plaster volume, with half the water volume of the inert material (marble dust) added. Encapsulation was performed via PVC molds with diameters equal to the electrode base and standardized heights of 3.0 cm, resulting in a final sensor height of 3.0 cm (Figure 2C). After 10 min, the PVC molds were removed, and the finished sensors were placed in an oven at 60 °C until completely dry.

Two types of electrodes were selected for sensor evaluation: 20 × 5 mm and 15 × 5 mm. Each electrode was subjected to the treatments, resulting in a completely randomized block experimental design, with four replicates for each treatment. A 2 × 5 factorial scheme was used, with two sensors made with 20 × 5 mm and 15 × 5 mm electrodes and five filling and encapsulation materials: coarse sand + plaster with 30% marble dust, fine sand + plaster with 30% marble dust, glass wool + plaster with 30% marble dust, fine sand + plaster with 30% fine sand, and coarse sand + plaster with 30% fine sand.

To calibrate the encapsulated sensors, after being assembled, they were placed in rings measuring 50 mm in diameter and 50 mm in height and filled with soil collected from the 0–30 cm layer. The soil was classified as a dystrophic argisol Red–Yellow Latosol (Santos et al., 2013), and its physical–chemical characteristics are shown in Table 1. With the sensor installed in the soil, the rings were saturated for 24 h, the electrical conductivity of each sensor was measured, and then the sensors were subjected to different voltages (SCHOLL, 1978; DELA, 2001).

Table 1. Physicochemical attributes of the soil material used to calibrate the sensors

Características químicas									
pH	MO	P	K^+	Na^+	Ca^{2+}	Mg^{2+}	$H + Al^{3+}$	PST	CEes
H_2O	g kg^{-1}	mg dm^{-3}	---------------$cmol_c\ dm^{-3}$---------------					%	dS m^{-1}
5,4	8,28	2,0	0,16	0,05	1,6	1,10	0,33	1	0,11

Características Físicas				
Fração granulométrica (g.kg^{-1})			Classe Textural	Ds
Areia	Silte	Argila		kg.dm³
776	24	200	Franco Arenoso	1,44

MO – Organic matter: Walkley -Black Wet Digestion; Ca^{2+} and Mg^{2+} extracted with 1 M KCl pH 7.0; Na^+ and K^+ extracted using 1 M NH_4OAc pH 7.0; Al^{3+} and ($H^+ + Al^{3+}$) extracted using 0.5 M CaOAc pH 7.0; CEes – electrical conductivity of the soil saturation extract; Ds - soil bulk density.

The sensors were subjected to the following stresses: 2, 4, 5, 10, 20, 40, 60, and 80 kPa. The first three were on a stress table (Figure 3A), which consisted of stainless steel funnels and inert material of fine sand or silt (marble powder) granulometry. For the other stresses, pressure cookers and Richards plates were used (Figure 3B), which consisted of a porous plate with one of its faces connected to the environment and the other to apply tension (pressure) in kPa inside the pan, removing moisture, which was equivalent to the matric potential to which the soil and the sensor were subjected.

Figure 3. (A) Tension and saturation table of the samples and (B) pressure cooker with soil rings on the porous plate

To evaluate the sensors, EC readings were taken at different voltages and treatments. The EC values were converted to relative EC values measured when the sensors were saturated (zero voltage) before being subjected to the tested voltages. A comparison was made between the replicates of each treatment and the voltage at which the EC changed. The resistance measurements were replaced with EC measurements because the readings from direct current multimeters did not stabilize, which did not occur with conductivity meters. Although portable, they have a full scale of 20 dS m^{-1}, requiring only one modification: replacing the load cell with two alligator clips to connect them to the sensor wires.

The sensors were evaluated by the coefficient of variation between the real and relative electrical conductivity readings. After the best sensor was identified, regression analysis was performed to identify the most appropriate model for evaluating soil water tension.

5 RESULTS AND DISCUSSION

When the plaster blocks and sensors were saturated several times, their absolute and relative electrical conductivity values varied between the saturation stages (Figures 4, 5, 6, and 7). In this case, the most stable sensors were those made with the same filling/encapsulation material or electrodes with larger spaces between the rings (20 × 5 mm) that had filled/encapsulated fine sand/gypsum + 30% marble. Thus, materials with a coarse texture inside the sensor and very fine texture on the outside, especially when the space between the rings is smaller, are more unstable to saturation. This observed behavior may have occurred because of the trapping of air bubbles in the saturation/resaturation process (DELA, 2001).

As plaster is a material that has difficulty obtaining the pore volume and distribution that produces uniform electrical resistance within the material, it is difficult to achieve saturation between the electrodes at pressures less than 33 kPa (SCHOLL, 1978).

This variation in the material interferes with the saturation of the sensors, making the calibration process difficult, as it would be necessary to make several points on a retention curve to use as variables in the calibration and, on the other hand, when they are uniform, they need only one point for calibration.

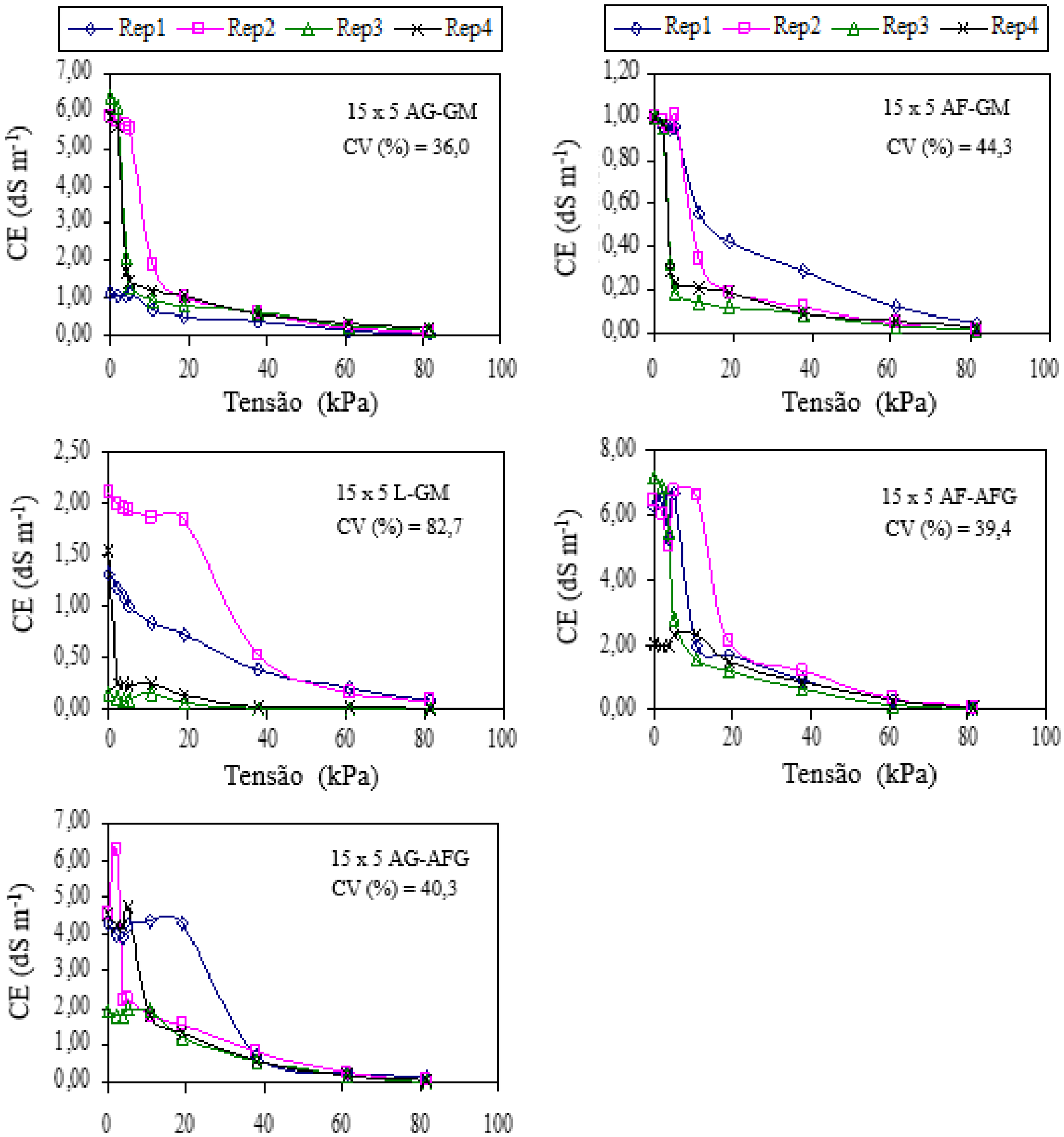
Errors related to temperature variations can be avoided or reduced in the field by always taking readings at the same time, preferably early in the morning, as during this period, the soil temperature does not vary between days, especially in tropical regions.

The 20 × 5 mm electrodes presented more uniform readings than the 15 × 5 mm electrodes did (Figures 4, 5, 6 and 7), probably due to the larger volume of the filler material and better uniformity of the internal humidity of the electrodes, resulting in more stable readings. For the sensors that had internal plaster, the saturation readings were more uniform, with a low coefficient of variation for saturation (Figure 5). However, in the high humidity range (low voltages), the sensors do not have the desired sensitivity for use in agriculture, especially for the management of localized irrigation systems, which operate at low voltages (less than 30 kPa).

The humidity sensors that presented greater stability in the readings and better sensitivity to low voltages were AF-GM (fine sand + plaster + 30% marble powder) and AF-AFG (fine sand + 30% fine sand + 70% plaster), which were associated with a 20 × 5 mm electrode (Figures 6 and 7), with an average variation of 4.7% between repetitions, under the different voltage conditions studied.

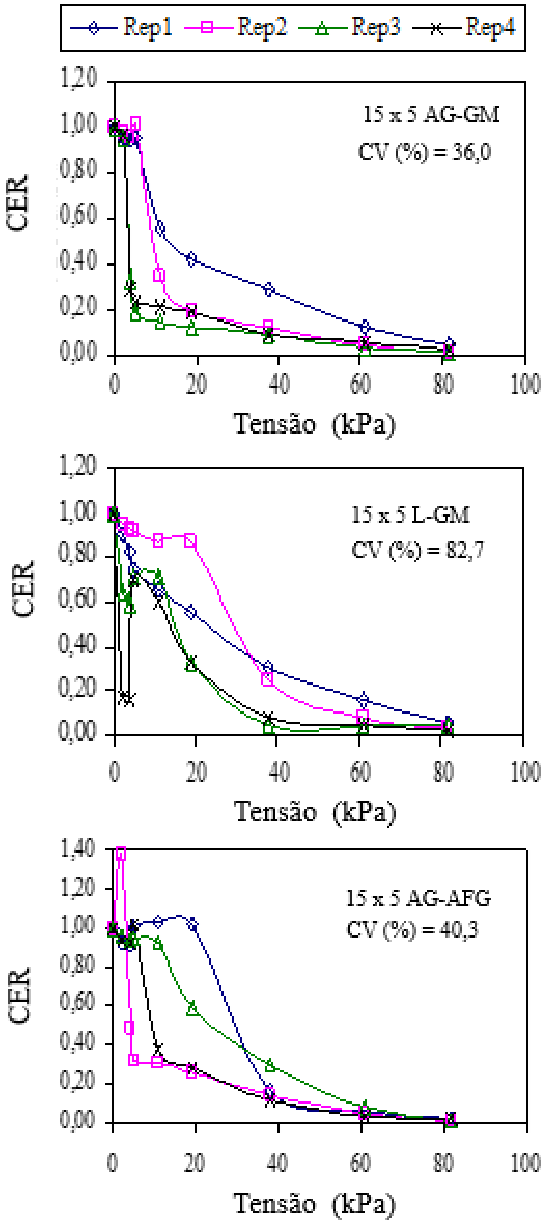
The fine sand combined with plaster presented smaller variations than plaster alone, which can probably be explained by the fact that the fine sand provides plaster with a larger pore volume, allowing this combination to produce uniform electrical conductivity within the material. However, the use of EC measured at different voltages (absolute EC) in relation to the EC measured when only the electrode was saturated (relative EC) did not significantly alter the behavior of the curves for the stable sensors. However, it has the advantage of obtaining values with less variation between the electrode types.

Figure 4. Absolute and relative electrical conductivities of 15 × 5 mm sensors subjected to different voltages at KPa.



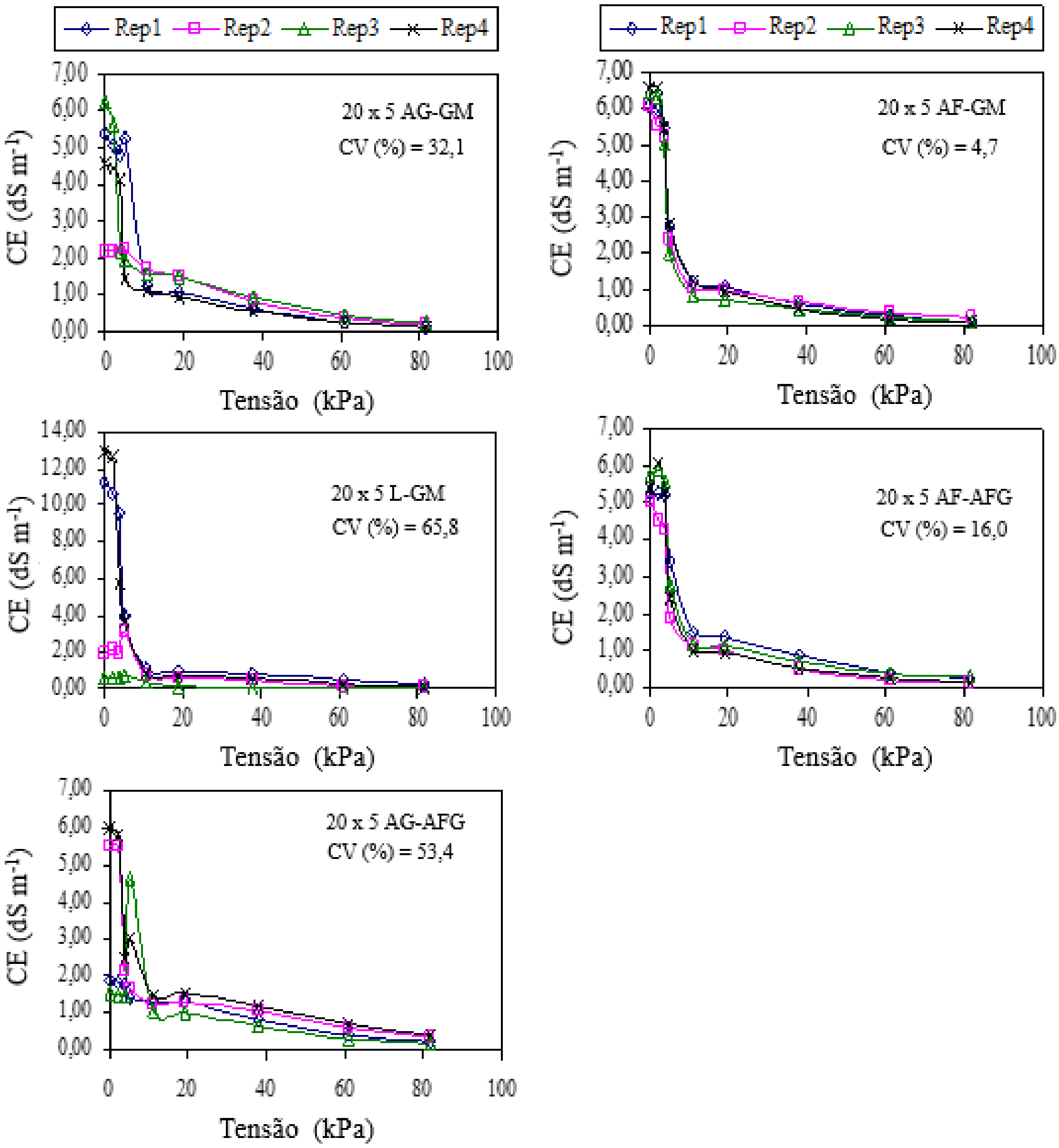
Note: 15 × 5 – Electrodes with external diameters of 15 mm and internal diameters of 5 mm; GM – Gypsum + 30% marble powder; L – Glass wool; AF – Fine sand (granulometry between 0.1 and 0.2 mm); AG – Coarse sand (granulometry between 0.2 and 0.4 mm); AFG – 30% Fine sand + 70% gypsum

Figure 5. Relative electrical conductivity (CER) of the 15 × 5 mm sensors subjected to different voltages at KPa.



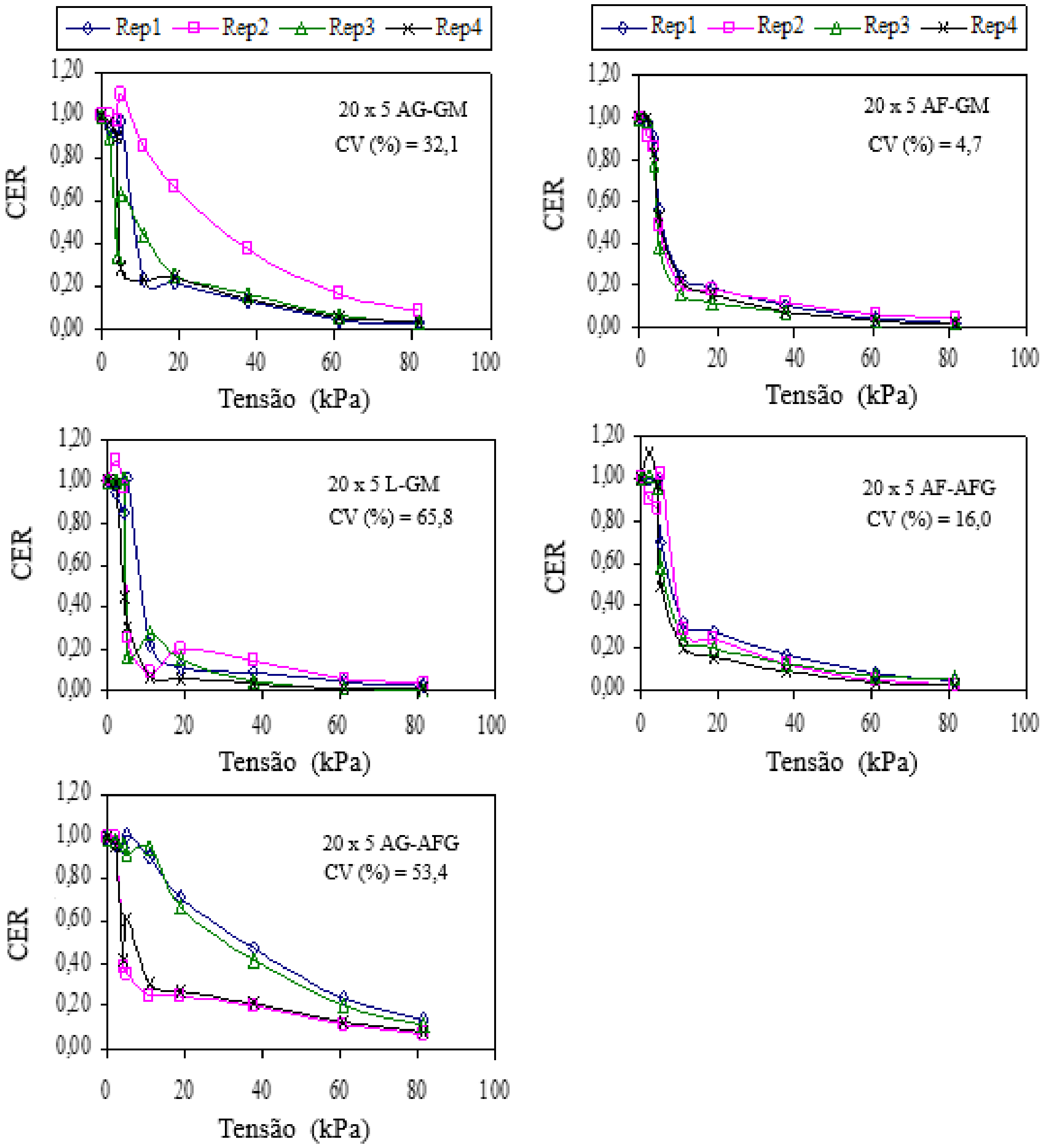
Note: 15 × 5 – Electrodes with external diameters of 15 mm and internal diameters of 5 mm; GM – Gypsum + 30% marble powder; L – Glass wool; AF – Fine sand (granulometry between 0.1 and 0.2 mm); AG – Coarse sand (granulometry between 0.2 and 0.4 mm); AFG – 30% Fine sand + 70% gypsum

Figure 6. Absolute electrical conductivity of the 20 × 5 mm sensors subjected to different voltages at KPa.



Note: 20 × 5 – Electrodes with external diameters of 20 mm and internal diameters of 5 mm; GM – Gypsum + 30% marble powder; L – Glass wool; AF – Fine sand (granulometry between 0.1 and 0.2 mm); AG – Coarse sand (granulometry between 0.2 and 0.4 mm); AFG – 30% Fine sand + 70% gypsum

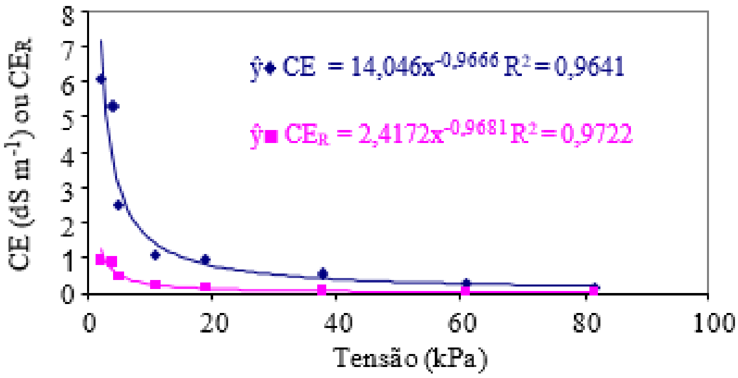
Figure 7. Relative electrical conductivity (CER) of the 20 × 5 mm sensors subjected to different voltages at KPa.



Note: 20 × 5 – Electrodes with external diameters of 20 mm and internal diameters of 5 mm; GM – Gypsum + 30% marble powder; L – Glass wool; AF – Fine sand (granulometry between 0.1 and 0.2 mm); AG – Coarse sand (granulometry between 0.2 and 0.4 mm); AFG – 30% Fine sand + 70% gypsum

When the saturation humidity was neglected, the power model, which was very close to the hyperbolic model, presented the best fit among the simple models with only one parameter. Figure 8 presents the equations of the power models that best fit the observed CE (absolute) or CER (relative) data under the studied stresses. The coefficients of determination (R^2) were 96.41 and 97.22% for the CE and CE $_R$, respectively. These models were similar to the models adopted in the adjustment of retention curves, such as the van Genuchten model.

Figure 8. Relationships between the CE (absolute) or CER (relative) and the voltages studied for electrodes measuring 20 × 5 mm, filled with fine sand and encapsulated with plaster + marble powder. The width was set to 10 or 15 cm.



With the electrical resistance method, the soil moisture measured with 20 × 5 mm electrodes, which were filled with fine sand and encapsulated with plaster + marble powder, was highly reliable (96.41%) for the EC measurements, which is higher than the reliability reported in the specialized literature for electromagnetic methods such as time domain reflectometry (TDR) and frequency domain reflectometry (FDR) (CRUZ et al., 2010; SILVA et al., 2012; BUESA-PUEYO, 2013; SOUZA et al., 2013; SCHWARTZ et al., 2013; SOUZA et al., 2016; GOMES et al., 2017; MATOS et al., 2017).

6 CONCLUSIONS

1. Sensors made with the same filling and encapsulation material, and even those that did not present great textural variation and electrodes with greater space between the rings, presented more uniform CE readings in terms of resaturation and similar voltage versus CE curves.
2. The 20 × 5 mm electrodes filled with fine sand and encapsulated with gypsum + marble powder were more sensitive to low voltages and provided more accurate soil moisture readings.

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