Effect of physical properties of granular sustainable-porous materials on water content measurements by using a low-cost sensor

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***Abstract* — Soil water content has a primary importance in several scientific fields involving the geotechnical, hydrological agronomic, ecological, and biological properties of the soil mass. In recent years, several techniques for the determination of soil water content in the laboratory and in situ have been proposed and developed. The application of these techniques and adopted measurement systems to different soil types is widely discussed in the literature, thus highlighting a nontrivial issue deserving further experimental research. This paper presents the results of the application to granular sustainable materials of a capacitive sensor originally developed for soil water content measurement~~.~~ In particular, the application regards coffee ground samples with two grain size distributions prepared dry and at increasing water content in the range of 5 – 25 %, at different initial voids rations. The effect of initial voids ratio and grain size distribution is also examined.**

Keywords— capacitive sensor, soil water content, coffee ground, initial porosity, grain size distribution

I. INTRODUCTION

Measurement of soil water content is of primary importance in the analysis and prediction of the behaviour of all types of soils, in both saturated and unsaturated conditions. In the last twenty years, significant advancements have been made in laboratory and field testing. The amount of literature on soil water content and suction measurements and related sensors is huge and involves several scientific fields (e.g. [1-3]). The applicability of these techniques to soils characterised by different physical and geotechnical properties is still an open question worth further investigation and experimental activities. A critical review is proposed in [4]. In that paper, the soil water content measurement techniques, their advantages and/or limitations, and the effects on such measurements of various soil-specific parameters such as mineralogical composition, soil fabric and structure, and salinity, are critically discussed.

The soil water content measurements can be classified into two methods/types: contact-based and contact-free methods [5]. Concerning the first method, direct contact of the sensor with the soil is strictly required. Capacitive sensors fall within this type (e.g. [6-9]), as well as Time Domain Reflectometry sensors (e.g. [10-12]) and electrical resistivity measurements (e.g. [13-14]). A wide review of such techniques is provided by [12] and more recently by [15] which presents a detailed summary of various soil water content measurement techniques and discusses the issues about the applicability of these techniques for different types of soils. On the other hand, the measurement of negative pore-water pressure (soil suction) is also of key importance in the analysis and prediction of unsaturated soil behaviour; first among all, the independent measurement of soil suction and water content is indispensable for the determination of the soil water retention properties. In this case, the specific literature covers several important studies ([3], [16-20]). The opportunity to count on independent measures of both soil water content and suction is therefore crucial, especially in geotechnical engineering applications.

Concerning capacitive sensors, two main classes of devices can be distinguished: parallel-plate or interdigital capacitive sensors. The two classes work with the same physical principle related to the fringing electric field that enters the soil with the sensor's capacitance mainly depending on the volumetric water content of the surrounding soil. The difference between these two types of devices is related to the electrode shape. In [21] the Authors follow an optimization process on three PCB-made interdigital capacitive sensor models evaluating the impact of geometrical parameters, such as finger thickness, finger separation, and substrate thickness. The three devices were tested in two sandy soils and two clay soils. The effect of geometric parameters such as electrode width and space between them before prototyping and testing their device is also analysed in [22].

In this paper, we present some preliminary results of two experimental sets of measurements performed in the laboratory, aimed at verifying the application of a capacitive sensor in wet samples of granular materials. The sensor, presented for the first time in [23], shares the same substrate with a custom readout circuit which measures the magnitude and phase of the sensor impedance when it is impinged in a soil medium. Here, to verify the standalone sensitive element performance, and the measuring system setup – including the sample preparation procedures – a peculiar granular material was chosen, i.e. a common ground coffee. This is a food waste with more than two million tons of coffee residues (e.g. coffee ground, pulp, and husk) produced per year worldwide. The reuse of food waste is part of our transition towards a circular economy model and spent coffee ground is under analysis in agricultural applications for its chemical properties, but also in engineering applications to be re-used as construction material [24-25] and road subgrade [26]. It is therefore of interest to investigate the behaviour of spread ground coffee concerning the electronic measurement of water content. In this study, the ground coffee samples were prepared at

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This research was partly funded by the Dipartimento di Ingegneria of the University of Perugia, Italy, grants: "Ricerca di Base 2021", and "Ricerca di Base 2022".

increasing gravimetric water content (GWC) in the range of 5% - 25% and in dry conditions. Two different grading curves were considered and samples were prepared at different densities.

II. INTERDIGITAL CAPACITIVE SENSOR FOR SOIL WATER CONTENT

The sensitive element (see Fig. 1) exhibits a custom layout and is built by using a commercial PCB double-sided technology. It takes the form of a laminated sandwich structure of conductive (one pair of copper electrodes in the bottom layer and one in the top layer) and insulating layers (FR4 in the middle to separate the two pairs of electrodes and solder mask on the top and bottom sides of the sensitive elements to protect the structure from the environment). The patterned electrodes placed on the top are short-circuited with those on the bottom by using vias and they can be electrically contacted using a pair of custom pads (grey regions without solder mask in Fig. 1 - (b)) housed on both sides of the structure. The layout of the two couples of electrodes is based on an interdigital architecture designed to maximize the performance of the device in terms of sensitivity [27]. TABLE I reports the vertical and planar dimensions of the sensor.

The equivalent admittance of the probe is:

$$Y = Y_{Re}(\varepsilon^*_{med}, \varepsilon^*_{PCB}) + jY_{Im}(\varepsilon^*_{med}, \varepsilon^*_{PCB}) \qquad (1)$$

where $j = \sqrt{-1}$ is the imaginary unit, and $Y_{Re}(\varepsilon^*_{med}, \varepsilon^*_{PCB})$ and $Y_{Im}(\varepsilon^*_{med}, \varepsilon^*_{PCB})$ are the real and imaginary parts of the admittance, respectively. They are a function of the complex dielectric permittivity of both the medium surrounding the device (ε^*_{med}) and the probe material (ε^*_{PCB}). In our application, the medium is the soil/granular material (solid-air-water) and its permittivity ε^*_{med} depends on its real permittivity (ε'_{med}), its electrical conductivity (σ_{med}), and the relaxation loss ($\varepsilon''_{med,rel}$) associated only with the relaxation of water [28]:

$$\varepsilon^*_{med} = \varepsilon'_{med} - j\left(\frac{\sigma_{med}}{\omega\varepsilon_0} - \varepsilon''_{med,rel}\right) \qquad (2)$$

where $\omega = 2\pi f$ is the angular frequency depending on the frequency (f) and ε_0 is the vacuum dielectric constant. We consider only the contribution of the electrical conductivity because the readout electronics operates in the range of 10 - 100 kHz [9], which is far from the frequencies at which water relaxation phenomena occur (~17 GHz).

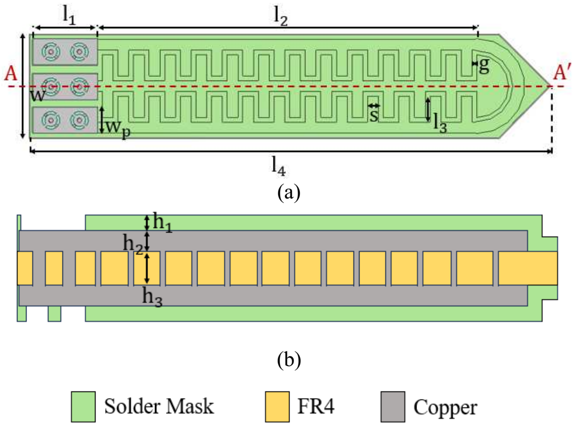


Fig. 1. Sensitive element layout: (a) Top/bottom view (in the figure $s = 2g$); (b) Vertical section AA'.

TABLE I. VERTICAL AND PLANAR DIMENSIONS OF THE SENSOR.

parameter	value (mm)	parameter	value (mm)
l_1	12.5	l_2	73.0
l_3	5.0	l_4	100.0
w	20.0	h_1	$\approx 20\cdot10^{-3}$
w_p	4.0	h_2	1.45
s	2.0	h_3	$\approx 50\cdot10^{-3}$

Finally, the material real permittivity ε'_{med} depends on the volumetric water content and the material/soil dry density and it is such a dependency that enables the measurement of the water content.

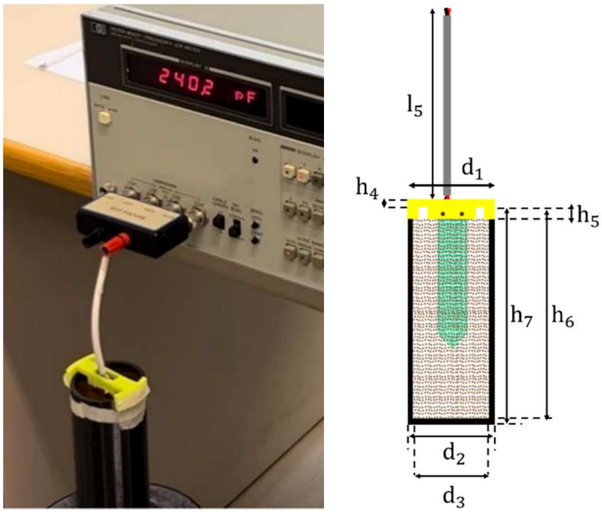
The results obtained in this paper highlight a consistent pattern of results in the measured frequency range although they do not yet allow us to extract the medium permittivity from the measured admittance. A deeper insight on the non-trivial relationship between the admittance of eq.(1), and the experimental capacitance and conductance, can be found in [9]. Regarding common ground coffee, some reference values can be found in [29], although for a wider range of applied frequencies (from 75 kHz to 5 MHz), that is overlapped to our range of interest just for a few frequencies. In [29], the Authors investigated the influence of bulk density at the same water content and found that both the real and imaginary components of the complex permittivity decrease as the frequency increases for all moisture contents. The real relative permittivity ranges from 2.25 to 4.5, whereas the conductance spans from 1 µS/cm to 55 µS/cm. A similar analysis is reported in [30] where coffee and several coffee-soybean mixtures are considered at a single frequency equal to 10 kHz. In this case, the real relative permittivity is in the range 1.3 - 4.3 whereas the electrical conductivity spans from 0.11 µS/cm to 0.87 µS/cm depending on the mixture roasting temperature and soybean powder concentration.

III. EXPERIMENTAL SETUP AND SAMPLE PREPARATION

In this work, measurements will be presented to analyse the functional behaviour of the interdigital sensor described above applied to two sets of ground coffee samples, at increasing values of water content. Below the adopted setup and measurement system will be reported, together with the procedure followed to prepare the coffee samples.

A. Experimental Setup

The hot electrode of the electrical potential source is tied to the central electrode of the PCB, capacitively coupled to the external electrode, which is connected to the ground potential. The electrodes are printed on both faces. The electric field originating from the electrodes intersects the sensor materials (FR4 and Solder Mask) and the medium surrounding the sensor. The potential source is applied using an HP4275A LCR meter (L is the electrical inductance, C is the electrical capacitance and R is the electrical resistance). The sensor is interfaced to the LCR meter using a twisted pair wire with a total length equal to l_5, as shown in Fig. 2. The two ends on one side of the wire are soldered to the sensor pads on the top face of the sensor, one to the central electrode and the other one to one of the two pads of the external electrode. The twisted pair wire affects the measurement of the sensor since it represents an additional electrical admittance in parallel to the sensor itself. For this purpose, a calibration of the LCR-meter is performed to take into account such contribution of the wires.



(a) (b)

Fig. 2. Experimental setup: (a) LCR-meter (model HP4275A), and (b) geometry of the laboratory equipment adopted for the sample setup.

The calibration is performed by using another identical couple of wires as the one soldered to the sensor: this is connected to the HP4275A and wired first as an Open Circuit and then in a Short Circuit configuration. Thus, the instrument measures the wires on each supported frequency upon these two configurations and stores the data to compensate for their contribution. The signal generated by the LCR-meter to supply the sensor is a sinusoid characterized by a peak voltage level, equal to 1 V, and a frequency varying in the range of 10 kHz - 10 MHz. Four frequencies were selected, namely 10 kHz, 30 kHz, 50 kHz, and 100 kHz. The sensor is then hand-driven into the granular material, in turn, compacted inside a cylindrical mould.

B. *Tested material*

The tested material is an organic coffee ground whose properties are summarised in TABLE II. The samples were prepared with two slightly different grain size distributions, shown in Fig. 3, namely types A and B. Type B-grain size distribution was obtained through a grinding process. For comparison, Fig. 3 also shows another set of grading curves reported in [31]. The dry unit weight is rather low (< 6 kN/m^3), compared to natural soils, leading to values of initial voids ratio e_0, not lower than 1.2. For each grain size distribution, the material was then mixed with tap water, characterised by electrical conductivity equal to 578 µS/cm at 20°C, at gravimetric water contents varying from 5 to 25%. Dry samples were also tested.

TABLE II. GRAIN SIZE CHARACTERISTICS OF TYPE A AND B GROUND COFFEE SAMPLES.

	type A	**type B**
G_s	1.365 [31]	
d_{10} (mm)	0.30	0.075
d_{50} (mm)	0.55	0.17
d_{60} (mm)	0.60	0.20
$U = d_{60}/ d_{10}$ (-)	2.00	2.67
GWC (%)	0 - 25	
$\gamma_{average}$ (kN/m^3)	6.21	
γ_d (kN/m^3)	4.01 - 5.93	
e_0 (-)	1.30 - 2.40	

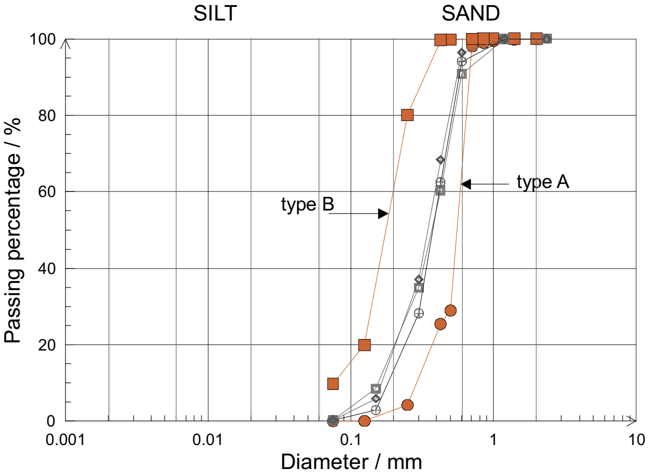


Fig. 3. Grain size distribution curves for ground coffee type A (brown with circle symbols) and ground coffee type B (brown with square symbols). The grey curves refer to data reported in [31].

C. *Sample setup and compaction*

After mixing the powder with a pre-determined amount of water, the mixture was divided into four portions. The material was then dynamically compacted inside a cylindric PETG (*PolyEthylene Terephthalate Glycol*) mould in n. 4 layers, by using a hollow cylindrical mallet of mass 853 g sliding along a vertical bar with a diameter of Φ = 40 mm. For the compaction of each soil layer, the mallet was allowed to drop between 3 and 10 consecutive times, to prepare samples at the same initial voids ratios, blowing from a height of ~17.5 cm by following a controlled and repeatable way. The top surface of each layer was scarified to ensure a good bond between layers. The mould was crafted with a Fused Deposition Modelling (FDM) 3D printer. After sample preparation, the sensor was inserted vertically into the sample from its top surface by means of a PLA (*PolyLactic Acid*) 'handle' also crafted with the 3D printer. The dimensions of the PETG mould and the PLA handle are reported in TABLE III.

IV. EXPERIMENTAL RESULTS

Measurements were carried out on samples prepared by using two ground coffee materials, A and B respectively, at six increasing values of gravimetric water content. Since the electrolyte concentration affects the measurement at the frequency of interest [23], the electrical conductivity of the tap water was regularly monitored (see Section III-B). Table IV reports the initial values of the voids ratio e_0 and porosity n_0 of two sets of A and B samples at increasing water content. For type A, a different number of blows was used to compact the material, yielding two different target values of voids ratio (A1 and A2).

TABLE III. DIMENSIONS OF THE EXPERIMENTAL SETUP.

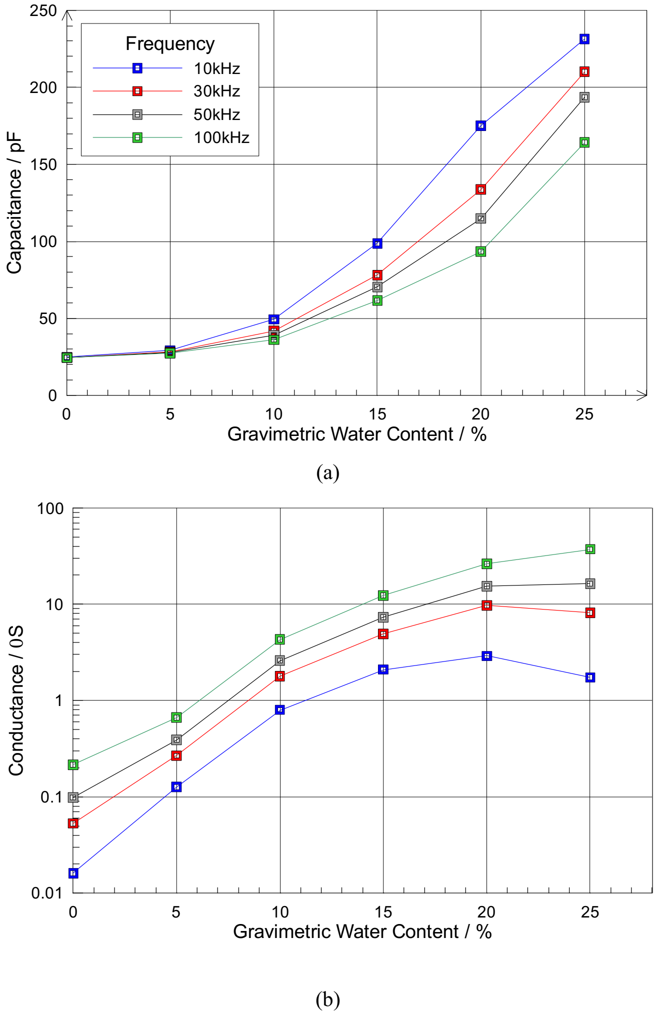
quantity	**value (mm)**	**quantity**	**value (mm)**
l_5	122.0	h_4	5.0
h_5	13.0	h_6	14.0
h_7	14.3	d_1	64.0
d_2	56.0	d_3	50.0

TABLE IV. EFFECTIVE VOID RATIO AND POROSITY VALUE OBTAINED AFTER THE PREPARATION OF THE THREE FAMILIES OF SAMPLES.

GWC (%)	A1		A2		B	
	e_0	n_0	e_0	n_0	e_0	n_0
0	1.98	0.66	1.58	0.61	1.31	0.57
5	2.00	0.67	1.96	0.66	1.31	0.57
10	2.19	0.69	1.49	0.59	1.39	0.58
15	2.35	0.70	1.54	0.60	1.49	0.60
20	2.31	0.70	1.54	0.60	1.62	0.62
25	2.36	0.70	1.52	0.60	1.71	0.63

A. *Sensor response to increasing water contents in coffee soil*

Measurements in sample A1 are shown in Fig. 4 in terms of gravimetric water content (GWC). For each sample, a frequency sweep was performed, and capacitance and conductance were measured. Measurements started with the sample at the lower water content. The sensor was then removed and driven in the samples at progressively higher water contents. The capacitance and the conductance both increase with increasing GWC. For a given water content, as the frequency increases, capacitance decreases while conductance increases.



(a)

(b)

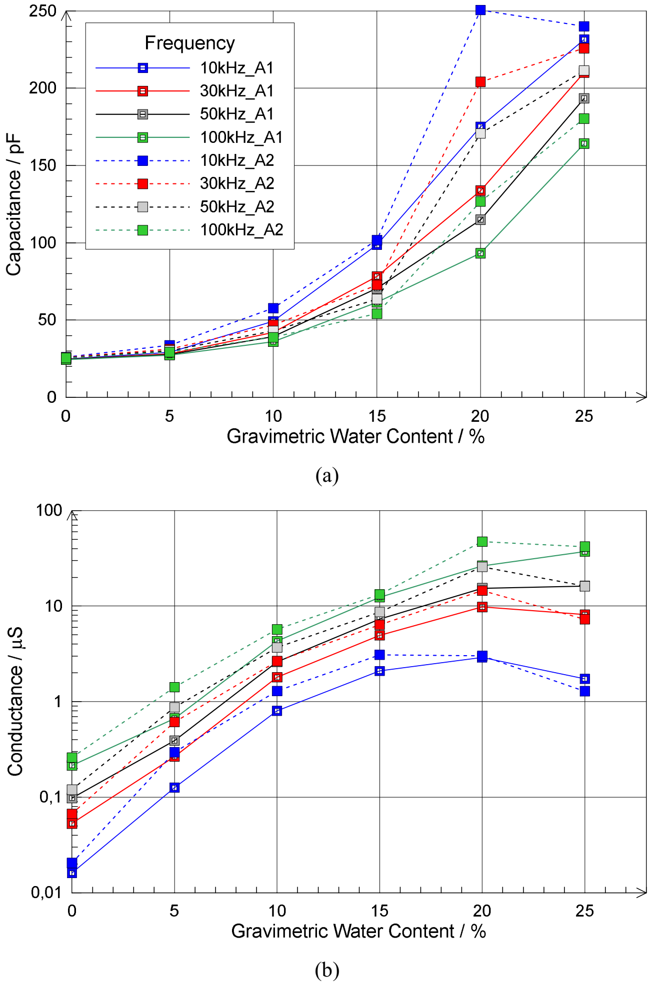
Fig. 4. (a) Capacitance and (b) Conductance measured by the sensor in coffee A1 samples as a function of the GWC for four values of interest.

However, at lower frequencies, conductance seems to report a maximum value after which the behaviour tends to decrease at a water content of about 20 %.

On the other hand, the increasing behaviour of the capacitance as the water content increases does not reach a maximum value in the considered range of GWCs. Moreover, at low-frequency values, the slope of the conductance curves (see Fig. 4 - (b)) seems to change suggesting the attainment of an approximately “stable” condition for the sensor. This is clear at 10 kHz, but more data are required to confirm this conclusion over the investigated range of water content. The sensor sensitivity depends on both the capacitive and conductive contributions. However, the capacitance sensitivity seems to be frequency-dependent and larger at low frequencies. In contrast with this, conductance sensitivity seems to be constant in frequency since the four curves seem to translate upward when frequency increases.

B. *Effect of the material compaction*

A second set of measurements was performed on denser samples, type A2, characterised by the same grain size distribution (see Fig. 3, circle symbols). The comparison with type A1 samples is shown in Fig. 5 in terms of capacitance and conductance.



(a)

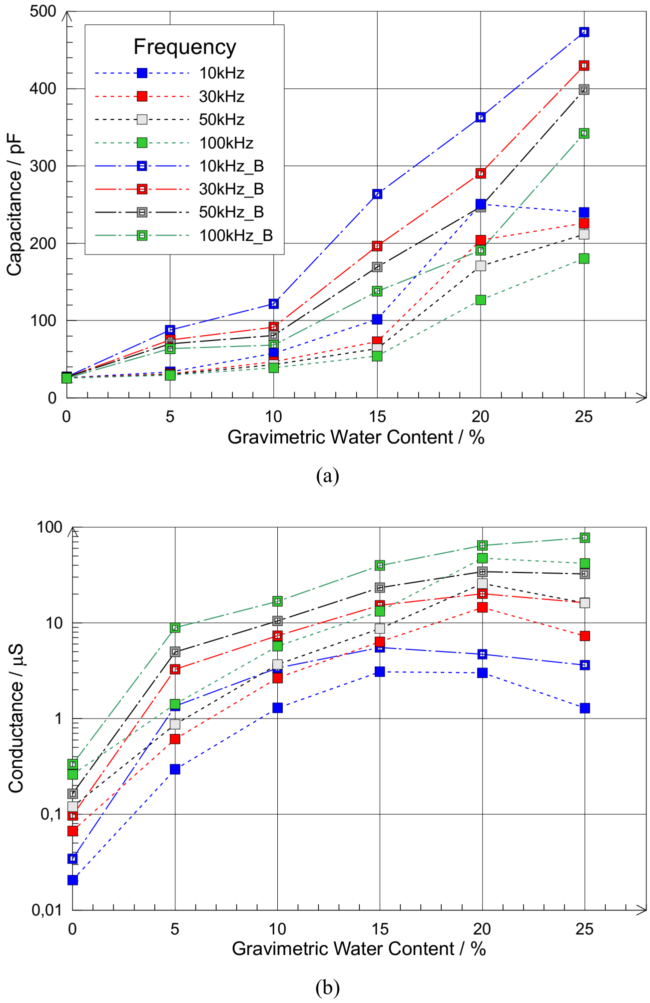
(b)

Fig. 5. Comparison between capacitance (a) and conductance (b) measurements in looser samples (type A1, continuous curves) and denser samples (type A2, dashed curves) as a function of the GWC in the frequency range of interest.

Fig. 5 - (a) shows a monotonic increase of the capacitance for both samples, with well spaced curves and the only exception of sample A1 at 10 kHz. This monotonic behaviour is a desirable feature when an intrinsic parameter like ε^*_{med} should be inferred from macroscopic measurements of capacitance and conductance through proper physical models. From Fig. 5 - (b), it is noted that: the initial voids ratio seems to affect the sensor conductance, i.e. the larger is e_0 (A1 samples), the higher is the value of GWC for which the "stable" condition occurs. On the other hand, for denser samples (type A2) the beginning of such condition can be appreciated only at the minimum value of applied frequency (10 kHz), for GWC of 15%. However, the curves of both looser and denser samples are rather similar.

C. *Effect of grain size distribution*

Another point of interest is the effect of particle size and grain size distribution. For this purpose, capacitance and conductance measurements made on samples denoted as type B (see Fig. 3) are compared with those obtained for type A2 samples. The two coffee mixtures differ only in their particle size, while their initial voids ratio is approximately the same (mean value, e_0 = 1.5) and porosity $n_0 \approx 60$ %. The comparison between sample types B and A2 is shown in Fig. 6, again in terms of capacitance (Fig. 6 - (a)) and conductance (Fig. 6 - (b)).

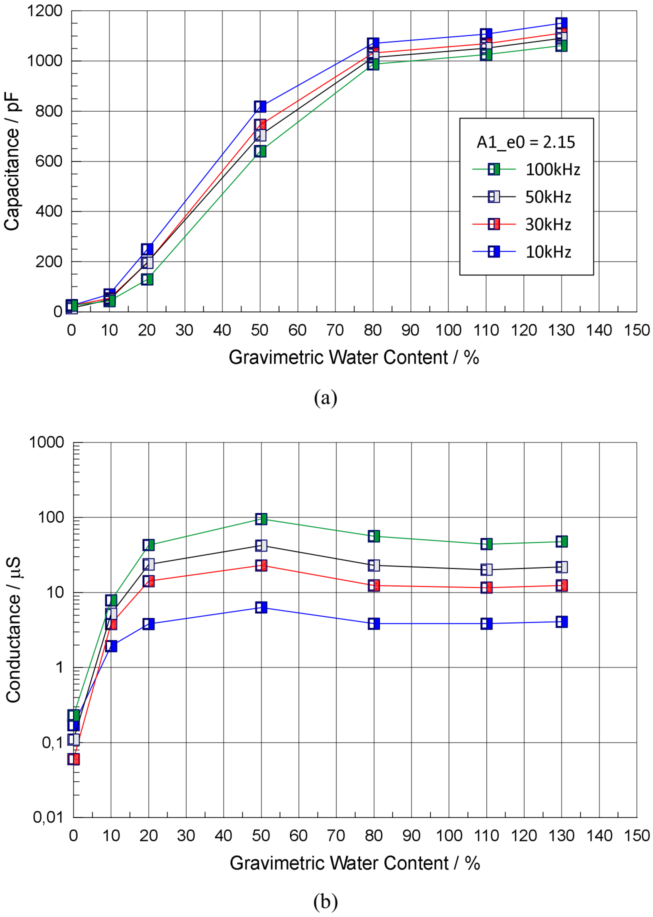


(a)

(b)

Fig. 6. Comparison between capacitance (a) and conductance (b) measurements in samples from family B (continuous curves) and family A2 (dashed curves) as a function of the GWC in the frequency range of interest.

In terms of capacitance, it is found that there are some clear differences between the two datasets, indicating that this type of measurement can distinguish different gradings. A global increase in the sensitivity of the sensor is observed for type B samples; secondly, for the same samples, the capacitance increases almost linearly with GWC, while for A2 samples the increase is less pronounced. When comparing the previous Fig. 5 - (a) with Fig. 6 - (a), the tendency of the capacitance to decrease at GWC larger than 20 % is no longer observed for type B samples. This evidence may suggest that for soil B characterised by smaller grain dimensions, the saturation condition could be reached for larger GWCs. When looking at Fig. 6 - (b) showing conductance vs. GWC, the observed sensor behaviour seems to depend on the explored range of water content. For water contents lower than 5 %, the conductance of type B samples registers a larger sensitivity than type A2 samples. On the other hand, when the GWC exceeds 5 % the concavity of the curves related to samples B is mitigated with respect to coarser type A2 samples. However, all these curves exhibit a maximum value in conductance, attained at GWCs which increase with applied frequency. Finally, to explore the sensor performance at larger water contents, close to the fully saturated conditions for the material, some further measurements have been conducted. In this case, looser coffee samples, type A1 (e_0 =2.15) were mixed with water at increasing values of gravimetric water content in the range 0 – 130%, thus approaching a saturation degree larger than 80%.



(a)

(b)

Fig. 7. Capacitance (a) and conductance (b) measured on looser coffee samples, type A1 (e_0 =2.15) for a wide range of GWC in the frequency range of interest.

The results shown in Figure 7 seem to confirm a proper functioning of the sensor, while showing the attainment of a "stable condition", starting from water contents larger than 80%.

V. CONCLUSIONS

For the particular type of granular material, i.e. ground coffee, explored in the present paper, capacitance, and conductance measurements, even accomplished in the limited frequency range of 10 - 100 kHz, showed a rather good ability to distinguish different initial material density (effect of voids ratio), grain size properties and water content. Different sensitivities of the sensor have also been found in different frequency ranges. Once the material characterisation - in terms of physical properties - is known, preliminary calibration measurements as a function of grading, porosity, and water content could be very helpful for defining AI algorithms able to extract the unknown parameters of the examined material. Concerning the investigated material, which is ground coffee, it should be underlined that from a circular economy perspective, its reuse in non-structural engineering applications might be a possible option. In this regard, the validation of electronic measurements employing a low-cost capacitive sensor is of some interest.

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