SMART CAPACITIVE MOISTURE SENSOR CALIBRATION IN MINERAL WOOL AND GREEN ROOF SOIL SUBSTRATE

by

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Original scientific paper
https://doi.org/10.2298/TSCI200217228K

The environmental benefits of green roofs have been widely recognized. In recent years, increasing attention has been paid to moisture management in the green roof systems. The moisture in the green roof has an influence on its thermal and hydrological performances. An accurate measurement of water content in green roof substrate is important for irrigation monitoring, optimal irrigation management, and plant growth. Knowing the performance and characteristics of the sensor for the chosen substrate layer in a green roof system is essential. This paper presents laboratory calibration of the capacitive moisture sensor in two types of the green roof substrate layer. The volumetric water content of several mineral wool and soil samples, with the water content from low until saturated, were measured using the gravimetric method and related to frequency obtained by the sensor. The results have shown that the capacitive moisture sensor has a good response to water content variation.

Keywords: *capacitive sensor, mineral wool, moisture measurement, soil, green roof*

Introduction

Water content is one of the most important measured properties in climate research, environmental science, agriculture, and several industries, including electronics, pharmaceutical, food, etc. Therefore, precise and reliable measurement of water content is essential in a wide range of scientific and technical fields. Over the last years, increasing attention has been paid to moisture management in the green roof systems. The environmental benefits of green roofs have been widely recognized. They reduce air pollution [1], energy consumption [2], urban heat island effect [3], and stormwater runoff [4]. The properties of green roof substrate are essential for achieving benefits that a green roof can give. The optimum green roof substrate needs to be lightweight, chemically stable, well-aerated, free draining, and able to supply water and nutrients to plants [5]. The moisture in green roof substrate has a vital role in the following processes: photosynthesis, transpiration, seed germination, plant growth, plant

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physiological health, and productivity. Water and dissolved mineral nutrients are absorbed from the substrate by plant roots and transported to the leaves through the plant tissues. Therefore, the lack of water in a green roof substrate effects on plant size and nutrition. However, too much water affects various metabolic processes inside a plant cell and causes the rotting of roots due to anaerobic conditions.

Mineral wool is a widely used material for thermal insulation in civil engineering. In extensive green roof systems, hydrophilic mineral wool is used as a soil substrate substitute. Hydrophilic mineral wool is a non-flammable lightweight, easy to install material that increases green roof water retention capacity. Mineral wool green roof substrates are several times lighter than other green roof substrates. Therefore, it is possible to install lightweight green roof systems with mineral wool in old buildings, where only minimum roof loads are allowed. Precise and reliable water content measurement of the substrate layer in a green roof system leads to an accurate determination of its thermal and hydrological performances. In addition, continuous monitoring of water content in green roofs is important for irrigation monitoring and optimal irrigation management, especially in semi-arid climates. Commonly, the automatic irrigation system for the green roof is connected with a rainfall sensor to prevent irrigation during precipitation events and equipped with a substrate moisture sensor to apply irrigation based on water requirements. Currently, there is a lack of research regarding the accuracy of different methods for moisture measurement in green roof substrates [6-8].

Moisture measuring methods

Various methods have been developed for measuring moisture in porous materials under laboratory conditions and moisture monitoring on the site. Classification, adopted previously by others, sets the existing methods of the water content determination into the following categories: gravimetric, nuclear-based, electromagnetic, tensiometer-based, hygrometric, and remote sensing processes [9, 10]. The gravimetric method also referred to as the thermo-gravimetric method, is the oldest, direct method for moisture measurement. This commonly used method for moisture measurement consists of comparing the sample weight before and after draying the sample in the oven to a constant weight. It is presumed that calculated weight loss is entirely due to water evaporation. This method is low cost and precise, however, it is destructive, labor intensive, time-consuming, and suitable only for laboratory applications. Neutron Scattering, Gamma Attenuation, and Nuclear Magnetic Resonance are nuclear-based methods. These methods are accurate and non-destructive, nevertheless, the high cost, the requirement of a certificate to operate, and radiation hazard limit the applicability on the site.

The study of dielectrics has revealed that water content can be determined using the properties of electromagnetic waves. Water's permanent dipole moment is high in comparison with other materials and as such water has a high dielectric constant of 80, while other soil constituents have dielectric constants of less than 5 when measured between 30 MHz and 1 GHz. In a mixture of water and dry soil, the resulting dielectric constant is between these two extremes, thus offering a mechanism for detecting the water content in the soil [11]. The resistive sensor, the capacitive sensor, the time domain reflectometry (TDR), and the frequency domain reflectometry (FDR) are the most commonly used sensors based on an electromagnetic technique. The TDR determines the dielectric constant of an object using an electromagnetic pulse, which is transmitted into the soil through a probe, buried in the soil. From the reflected signal, the propagation velocity can be calculated. The FDR is similar to TDR but estimates soil water content through measuring changes in the frequency of a signal as a result of soil dielectric properties [12]. The main advantage of both methods is that they are non-destructive, but in comparison with TDR, FDR can provide less accurate results due to sensitivity to soil characteristics.

The primary method for measuring capillary tension in soil involves the use of the tensiometer, which directly measures matric potential. The main disadvantage of the tensiometer is that it functions only from zero to approximately –0.8 bar, which represents a small part of the entire range of available water. The lower water limit for the good growth of most plants is beyond the tensiometer range, therefore this method is not applicable for green roofs. Electrical resistance hydrometers that utilize chemical salts and acids, aluminum oxide, electrolysis, thermal principles, and white hydrosol are used to measure relative humidity. Since the thermal inertia of a porous medium depends on water content, soil surface temperature can be used as an indication of water content. The measured resistance of the resistive element is a function of relative humidity. The hydrometers comprise a complex and expensive system, impractical for onsite usage.

Ground Penetrating Radar (GPR) is based on the same principle as TDR, but the measurements can be taken without direct contact between the sensor and the soil. It uses electromagnetic energy with frequencies generally varies between 50 and 1200 MHz to image the subsurface [13]. The GPR is an unfitting method for saline soils, where penetration depths are typically less than 25 cm. Satellite remote sensing provides soil moisture observations globally and in larger areas, so it is more suitable for hydrological studies. The most commonly used devices are capacitance sensors, which will be further discussed thoroughly.

Capacitive moisture sensors

Previously mentioned methods for water content measurement have some limitations in terms of practical application. Typically they are expensive, invasive, labor intensive, and time consuming or have potential health risks like nuclear-based methods. Among the sensor types available on the market, capacitive moisture sensors offer numerous advantages associated with cost, time, and possibility of measurement automation. These moisture sensors are suitable for non-invasive, frequent moisture measurement in different porous materials. In the last decades, capacitive moisture sensors have found their applications in a wide range of technical fields [14-16]. This moisture sensor type is also used to estimate the water content of agricultural products like grains [17] and for monitoring of soil water content in order to optimize the irrigation [18]. Capacitive sensors are relatively simple compared to RF-based techniques and do not have health risks compared to radiation-based methods. Furthermore, they do not require direct exposure of the metal electrodes, which decrease the erosion of the electrodes, compared with resistive sensors.

To understand the performance and adjust accuracy expectations of capacitor type moisture sensors, some basic operating principles should be revised. A classical image, fig. 1, of two closely spaced, parallel metal plate electrodes with connection wires is well-suited for the consideration.

Upon switching the connection selector from neutral (B) to (A) position, the plates will, provided by the source of voltage, V, become loaded with the same quantity of the electric charge, Q, of the opposite signs. The capacitance, C, defined as Q to V ratio, of such a condenser is:

$$C = \frac{\varepsilon S}{d} \tag{1}$$

where S is the surface of a plate, d – the distance between the pair, and ε – the static permittivity of the medium, dependant on the type of medium.

The permittivity in a vacuum is known constant $\varepsilon_0 \approx 8.85 \cdot 10^{-12}$ F/m, while the value of ε for any other dielectric medium is greater than ε_0, and is generally dependable on the temperature and frequency of the electric field. Non-dimensional ε_r, called relative dielectric constant or relative permittivity, is defined as the permittivity of a dielectric material relative to the permittivity of a vacuum:

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0} \tag{2}$$

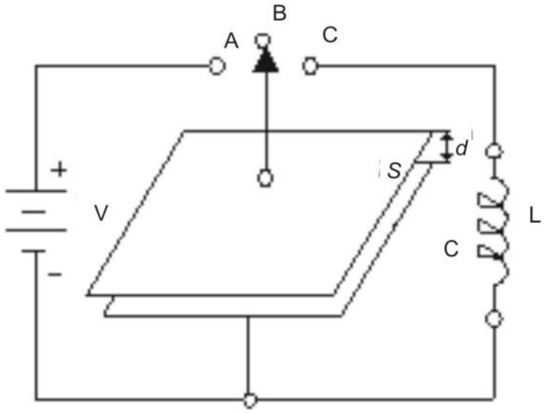

Figure 1. Schematic diagram of a parallel plate capacitor

Polarized dipoles in the structure of dielectric get oriented in such a manner to neutralize the external electric field as much as possible, and the value of ε_r reflects their effectiveness. Materials with a higher relative permittivity have higher insulating properties than a material with a lower relative permittivity. Moisture sensors based on the capacitance principle indirectly measure the water content of the material by measuring the change in relative permittivity of material and hence the change in capacitance. Water has a high relative permittivity (80 at 20 ºC) in comparison to air – 1, solid components of the soil – 2-5, and dry mineral wool it is around – 2. Therefore, small changes in the water content of these materials mean considerable changes in their relative permittivity. Switching the selector to a position (C) would make the circuit of charged capacitor and coil (of fixed inductance, L) to oscillate with a sinusoidal period:

$$T = \frac{1}{f} = 2\pi\sqrt{LC} \tag{3}$$

Since it is fairly easy to accurately measure a sinusoidal frequency or its period, by measuring period T_0:

$$T_0 = \frac{1}{f_0} = 2\pi\sqrt{LC_0} \tag{4}$$

and T (or frequency, $f = 1/T$) it is possible to calculate the percentage of water in the capacitor. It should be emphasized that the capacitance of the soil is a not a simple function of the water content, it also depends on the soil temperature, texture, and electrical conductivity [19, 20]. Contact conditions and an air-gap between the capacitive sensor and the soil can affect the sensor readings and accuracy of moisture measurements [21]. In addition, sensor-to-sensor variability can lead to errors in moisture determination with capacitance sensors [22]. The moisture sensors require substrate-specific calibrations due to the different properties of the substrates that influence sensor readings. Since the capacitive moisture sensors measure the change in frequency due to the change in permeability, sensor calibration against a gravimetric method has to be performed.

There is a need for an accurate, non-destructive, and low-cost sensor for in-situ water content measurement in green roof systems. Since extensive green roof substrate is only about 4 cm thick, the dimensions of moisture sensor to be installed are limited. The majority of commercial moisture sensors are planned to be applied in agriculture and are unsuitable for the substrate layer in extensive green roof systems, due to sensor shape and length. There is a lack of research regarding the accuracy of moisture sensors in green roofs especially in green roofs with a mineral wool substrate. This paper describes how to develop and evaluate calibration equations of sensor frequency and water content in mineral wool and soil substrate for green roof systems. The obtained calibration equation of the smart capacitive sensor will be used in further research of the green roof system with mineral wool and soil substrate layer.

Measurements

Two types of substrate were chosen for this experiment, the mineral wool and commercially available Compost soil obtained from a local producer. The water content in substrates was determined, according to standard SRPS EN ISO 12570:2009 [23]. This method consists of sample material weight measuring before drying, drying it to constant weight, and finding the loss in sample weight after oven drying. Mineral wool samples having dimensions of 16 × 16 × 4 cm and a density of 50 kg/m^3, and 500 g of soil were packed in containers of known volume. The soil was sieved through a 2 mm mesh to remove aggregated soil clumps. The mineral wool and soil were first oven-dried at 105 ºC and 80 ºC, respectively, for 24 hours to remove water, and then cooled to room temperature. For soil with high organic matter, it is recommended that drying temperature does not exceed 80 °C [24]. Mineral wool and soil samples with different water contents were prepared by adjusting the water content gravimetrically, to achieve water content from low to high until saturated. For each substrate type, the measurements campaign was performed for five volumetric water contents.

Starting from the oven-dried samples, a known amount of distilled water was added incrementally. The soil was well mixed to ensure homogenous water distribution. Then the containers were covered with plastic wrappings to avoid water loss and left for 24 hours to ensure a homogenous state. Frequency in mineral wool and soil was measured using a smart capacitive sensor for continuous moisture measurement, shown in fig. 2. The sensor was inserted vertically in the middle of the samples, so distances to the edges of the container were sufficiently large, to capture the entire zone of sensor influence. Full contact between the sensor and the substrates was achieved to prevent air-gaps around the sensor. A combination

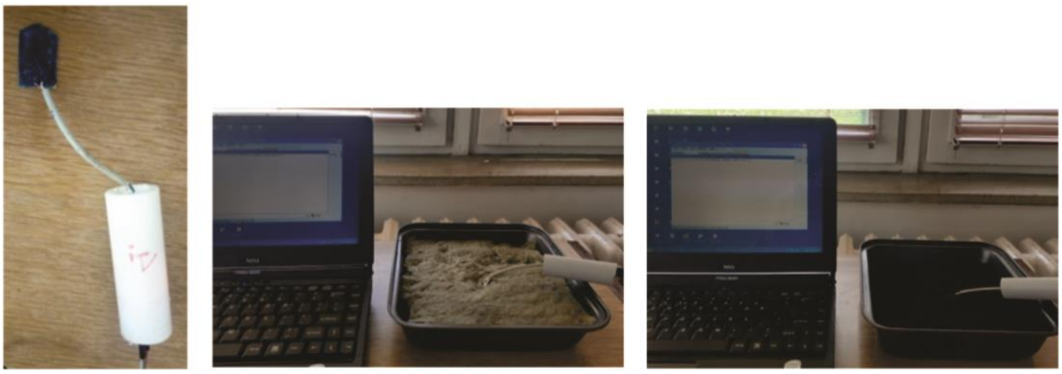

Figure 2. (a) Smart capacitive moisture sensor, (b) moisture measurement in the mineral wool sample, and (c) moisture measurement in the soil sample

of mineral wool, air, and water is yet further away from an ideal homogenous material than any type of soil. The frequency was continuously measured until it reaches the stabilized value**,** with an interval of 1 minute and recorded on a computer. Before each sample measurement, the sensor probe was cleaned and normalized by recording the readings in the indoor air.

After frequency measurement, the samples were weighed on a digital lab scale with an accuracy of 0.01 g, and the weight of wet samples was recorded. Finally, the samples were oven dried to a constant mass at 105 ºC and 80 ºC, respectively. Water can evaporate from the wet samples and can be picked up by the drier ones causing an error in weighing, due to a temporary increase in water content. Therefore, each sample was separately dried in the oven. After oven drying, the samples were placed into desiccators until their temperatures were cooled to approximately 30 °C, and then reweighed. Maintaining a consistent environment is essential to ensure accurate and reliable measurements. The measurements were conducted in laboratory conditions with an air temperature of 23±1 °C and relative humidity of approximately 55%. The water content may be expressed by weight (gravimetric water content) as the ratio of the weight of water to the weight of the dry sample. The gravimetric water content in dry weight basis was calculated:

$$GWC = \frac{m_{\mathrm{wet}} - m_{\mathrm{dry}}}{m_{\mathrm{dry}}} \tag{5}$$

The water content may be expressed by volume (volumetric water content) as the ratio of water volume per volume of the dry sample. The conversion into a volumetric equivalent can be done by multiplying the gravimetric water content by the dry bulk density of the samples, with knowledge of water density:

$$VWC = GWC\frac{\rho_{\mathrm{b}}}{\rho_{\mathrm{w}}} \tag{6}$$

Often, GWC and VWC are expressed as a percentage rather than a fraction.

Results and discussion

Both calibration sessions, with the mineral wool and Compost soil samples, aimed at providing a medium-specific relation of the capacitance sensor output frequency versus volumetric water content, were done at five measurement points. For both materials, the model that better fits calibration points is graphically presented, along with 95% confidence intervals. The obtained model, which describes the relation between the volumetric water content in mineral wool and the sensor output frequency, is given in a form of the second-order polynomial and displayed on the fig. 3. It is apparent that output frequency gets higher for dryer samples, as it is theoretically expected, close to the value of oscillating frequency obtained in the indoor air.

As the calibration curve was formed based on the measurement series, a 95% confidence interval was formed for it. The goal of forming this interval is to establish the range in which the points of the series should be found with a probability of 95%. The lower and upper limits of this interval are obtained basically by shifting the calibration curve by –0.0990 and +0.0990, respectively. High values of determination coefficient, R^2, and adjusted determination coefficient, adjusted R^2, as well as the low value of root mean square error (RMSE), presented in tab.1, indicate good representativeness of the proposed model. The adjusted coefficient of determination shows that 94.70% of the variability of the mineral wool moisture is

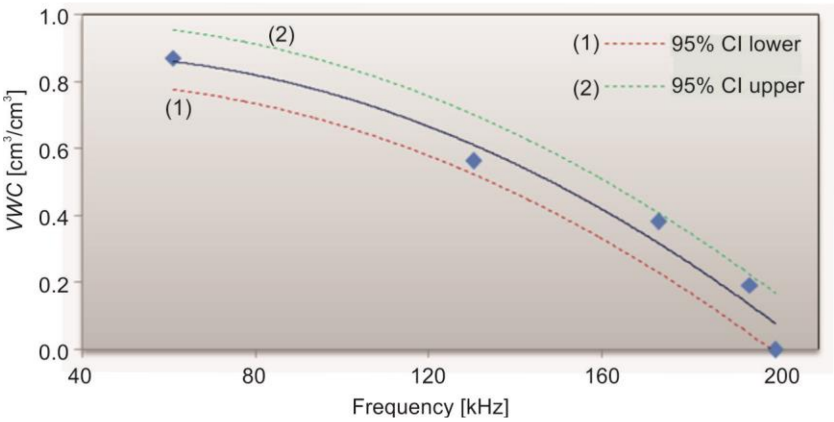

Figure 3. Sensor measurements and calibration curve in mineral wool

described by the model, while the average absolute deviation of the observed from the predictive values is small and amounts to 5.14%. These values confirm that the calibration curve model fits the obtained measurement values well.

Table 1. Parameters of calibration functions (mineral wool)

Volumetric water content in mineral wool	Function (2rd order polynomial) $y = ax^2 + bx + s$ $y = VWC$ $x = f$	$a = -4.34375 \cdot 10^{-5}$
		$b = 6.72407 \cdot 10^{-3}$
		$c = 467303 \cdot 10^{-1}$
	R^2	0.9602
	Adjusted R^2	0.9470
	RMSE	0.0514
	Confidence level (95%)	0.0990
	Function (linear) $y = ax + b$ $y = VWC$ $x = f$	$a = -4.62892 \cdot 10^{-3}$ $b = 1.0748$
	R^2	0.8570
	Adjusted R^2	0.8093
	RMSE	46.6580

The second model that describes the basic relationship between the mineral wool water content and the sensor output frequency, also presented in tab.1, is a linear function. Although this model doesn't provide as good approximation of the measurement data as the first one, it suites well to indicate the interdependence of observed phenomena. As the value of the linear slope suggests, an increase of the sensor output frequency by 1 kHz roughly corresponds to a reduction of volumetric water content in the mineral wool sample by 0.00463 cm^3/cm^3. The following graph, fig. 4, presents the model based on calibration points for the sensor output frequency and volumetric water content in Compost soil as well as the 95% confidence interval of the obtained curve.

The third-order polynomial is chosen, whose coefficients are given in the tab. 2. Considering the high value of adjusted R^2 = 99.68% and a low value of $RMSE$ = 1.11%, a good fit of the curve to the measurement data is indicated. The lower and upper limits of the 95% confidence interval are shifted by –0.0412 and +0.0412 from the calibration curve, respectively. Based on the linear model presented in the table below, a decrease of the volumetric water content in compost soil samples by 0.00293 cm^3/cm^3 corresponds to the output sensor frequency increase by 1 kHz.

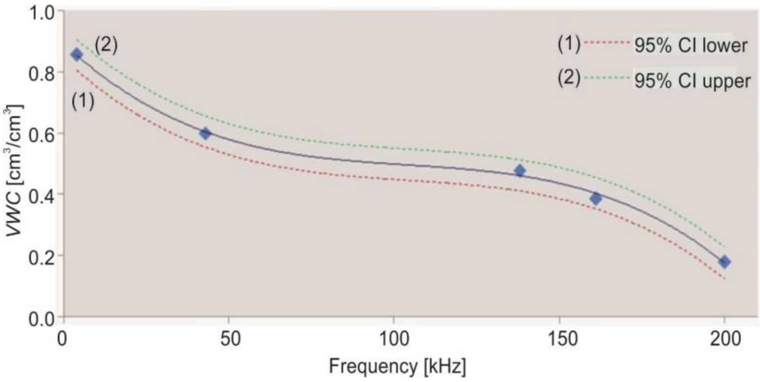

Figure 4. Sensor measurements and calibration curve in Compost soil

Table 2. Parameters of calibration functions (Compost soil)

Volumetric water content in Compost soil	Function (3rd order polynomial) $y = ax^3 + bx^2 + cx + d$ $y = VWC$ $x = f$	$a = -2.87773 \cdot 10^{-7}$
		$b = 8.99455 \cdot 10^{-5}$
		$c = -1.00688 \cdot 10^{-2}$
		$d = 0.894103$
	R^2	0.9976
	Adjusted R^2	0.9968
	RMSE	0.0111
	Confidence Level (95%)	0.04122
	Function (linear) $y = ax + b$ $y = VWC$ $x = f$	$a = -2.93413 \cdot 10^{-3}$ $b = 8.20526 \cdot 10^{-1}$
	R^2	0.9238
	Adjusted R^2	0.8984
	RMSE	0.0622

Conclusions

Water content in green roof substrate is a significant factor that has an influence on its thermal and hydrological performances. In this paper, with the objective of calibrating smart capacitive moisture sensor to work in a two substrate type for the green roof (mineral wool and Compost soil), calibration curves have been obtained. Obtained results indicated that calibration equations developed for the mineral wool and Compost soil were second and third order polynomial, respectively. According to the obtained results, the coefficient of determination, R^2, and the adjusted determination coefficient, adjusted R^2, were 0.9602 and 0.9470 for mineral wool and 0.9976 and 0.9968 for soil, indicating that models for calibration curves fit the obtained measurement values well. They were significantly correlated, with a small RMSE (5.14% for mineral wool and 1.11% for soil), suggesting that capacitive moisture sensor has good response to water content variation in mineral wool and soil samples.

Obtained calibration equations will be applied to the reading of the sensor in continuing green roof research. The moisture sensor performance was verified in the laboratory conditions. Therefore, in situ sensor calibration under environmental conditions is required. Also, the influence of substrate temperature variations on sensor output should be considered in further research.

Acknowledgment

This paper was produced under projects: Improving the energy performance and the indoor air quality of educational institution buildings in Serbia with the impact on health-III42008, which is financed by the Ministry of Education, Science and Technological Development of Serbia.

Nomenclature

C – capacitance [F]
F – frequency [kHz]
GWC – gravimetric water content [kg_{water}/kg_{dry}]
m_{dry} – dry sample mass [kg]
m_{wet} – wet sample mass [kg]
VWC – volumetric water content [cm^3/cm^3]

Greek symbols

ρ_b – dry bulk density [kgm^{-3}]
ρ_w – water density [kgm^{-3}]

Subscripts

b – bulk
w – water

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Paper submitted: February 20, 2020
Paper revised: July 10, 2020
Paper accepted: July 24, 2020