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APPLICATION OF DIELECTRIC BASED CAPACITANCE SENSOR TO MOISTURE CONTENT MONITORING IN MASONRY STONES

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ABSTRACT

The health of masonry structures is significantly influenced by moisture content. Effective approaches for measuring moisture content inside the masonry are a challenging task. Dielectric permittivity of the masonry materials is identified as an indicator that reveals the moisture content since the dielectric constant of water is much higher than that of the masonry materials. The dielectric constant can be directly measured through capacitance measurements using the material of interest as the dielectric medium. While many commercial capacitance meters, impedance analyzers and network analyzers are available for the capacitance measurement, the in-situ moisture content measurement instruments for masonry materials are still underdeveloped. This paper reports our work in addressing the needs of the in-situ monitoring of the moisture content in masonry stones. A handheld LCR meter and a wireless capacitance measurement system were selected as the moisture measuring instruments because they are inexpensive and easy to use in the field. Two planar capacitance sensors with fringing electric fields for the moisture sensing were chosen based on their simplicity and easy installation in masonry materials. The measured capacitances using the LCR meter and the voltages from the wireless data logger system correlated very well to the corresponding moisture content, suggesting the calibration of both instruments is practical for the in-situ moisture monitoring of masonry stones. The frequency dependence of the capacitance was investigated in order to understand how the complex dielectric permittivity of the saturated masonry stones affects the moisture content measurement. The results suggest that a higher measuring frequency for the instruments is preferable for measuring the relationship between the capacitance and moisture content because of the significant reduction in the interfacial dielectric polarizations and the double layer capacitance effect. The electrical conductance measurement indicates that the high conductance induced by the moisture content could introduce difficulties in capacitance measurements, especially with the wireless measurement system. The moisture-insulated and non-insulated electrodes of the capacitance sensors were tested regarding their influence on the capacitance measurement in relation to the moisture content. The results suggest that the fringing field capacitors with a very thin moisture insulating coating on the electrodes results in a better correlation between the capacitance and the moisture content when the LCR meter and the wireless sensing system are employed. This work demonstrates the feasibility of using planar capacitance sensors for in-situ moisture content monitoring in masonry stones with the wireless data logger system.

KEYWORDS

Moisture content, capacitance moisture sensor, dielectric permittivity, wireless sensing, masonry stone.

INTRODUCTION

Moisture content has a significant impact on the health of masonry materials and structures. The primary sources of moisture can be attributed to moisture absorption due to high humidity or liquid water from wind-driven rain penetrating the external wall. Excessive accumulation of moisture can result in structural damage by initiating and aggravating decay and corrosion of the masonry materials. To maintain the health of the construction materials and structures, the practical information of the moisture induced problems requires effective moisture measurement instruments, especially instruments for in situ measurement of the moisture content in masonry materials (Camuffo *et al.* 2012; Phillipson 2007).

Due to the complexity of the mixture of masonry materials and moisture, it has been a challenging task to develop standard in-situ measurement instruments for measuring moisture content in masonry. A number of physical properties are used to measure moisture content in materials, such as, weight, electric properties,

thermal properties and nuclear scattering and resonance properties (Saïd 2007). The weight-based method, called the gravimetric method, is the most simple and accurate, but impractical for field measurements. As a result, this method is mainly used in laboratory testing and for calibration of moisture measuring instruments. Electric-based methods are most widely used in determining the moisture content of soils, grains, lumbers and masonry materials through the measurement of electric resistance, capacitance and impedance of the materials of interest. Other methods are often limited to certain conditions (TenWolde 1985).

The porosity of masonry materials leads to the storage of moisture. Water molecules interact with the various mineral component constituents, resulting in complex mixtures of moisture and minerals that change the electric properties of the material. The dissolved molecules and ions carry mobile electric charges that greatly enhance the electrical conductance of the materials. The electrical resistance usually changes with the moisture content in a logarithmic relationship (Healy 2003). The resistance based moisture meters are widely employed due to their simplicity and low cost, however, measurement accuracy and their applications are constrained with the complexity of the materials, ionic polarization and difficulty in instrumentation dealing with large resistance ranges (Saïd 2007). Besides the conductance, the presence of moisture also changes the dielectric property of the materials since water has a much higher dielectric constant than that of the masonry materials. The dielectric constant of the material increases with the moisture level. The change in the dielectric constant provides an electric method to measure the moisture content. Many measurement techniques are used to determine the dielectric constant, such as lumped circuit, resonator, transmission line and free-space methods (Venkatesh *et al.* 2003). The method of choice depends on the materials of interest and the measuring frequency. The measurements are often accomplished by employing expensive instruments such as a network analyzer, impedance analyzer and spectrum analyzer. An example of the dielectric based moisture measurement is the time domain reflectometry (TDR) method; the principle is based on the dielectric induced time difference when electromagnetic waves propagate across the interfaces of different materials. This technique has been extensively explored both in laboratory and industries for applications, such as, soil moisture measurement (Stacheder *et al.* 2009; Ryyniinen 1995) and biosystems (Venkatesh *et al.* 2003) as well as in rocks (Nover 2005). The direct electric measurement of the dielectric constant is to measure capacitance. The capacitance method requires adequate electric circuit modeling considering both the physical and electrical nature of the materials and the measuring frequency of interest. For the measurement of the moisture content in masonry stones, capacitance can be measured using the stones as the dielectric medium of the capacitor. The saturated stones have a higher dielectric constant than the dry stones. Thus, the induced capacitance change can reflect the amount of the moisture inside the stones.

To address the needs of in-situ monitoring of moisture content in masonry, this work has been directed to find better tools for moisture content measurement. Our previous investigation in evaluating the moisture content inside masonry stones has indentified the dielectric based capacitive moisture sensing method as the best choice (Zhao *et al.* 2011). Building on our previous research, this work has further tested the applicability of two types of capacitor sensors and two types of measurement instruments. The capacitance sensors are constructed to use the fringing electric field to sense the moisture in the materials. The instruments include a handheld LCR meter and a wireless capacitance sensing system. Also, the influence of the measuring frequency on the dielectric properties of the moist masonry stone, the effect of the interface of the sensing electrodes with the moisture-stone mixture and the moisture/ion transport behavior in the stone were studied in order to better understand the dielectric related capacitance behaviors of the masonry stones. By establishing a relationship between the capacitance and moisture content in masonry stones, this work is expected to result in the application of these capacitance sensors and the instruments for in-situ moisture content monitoring in masonry walls. Additionally, the wireless measuring system is very useful for monitoring the moisture conditions of masonry structures where access is difficult.

DIELECTRIC BASED MOISTURE MEASUREMENT

Dielectric Properties

Masonry stones from natural sedimentary rocks are a very important and valuable construction material in buildings, especially in heritage structures. The structure of the stones is usually a non-crystalline, heterogeneous and disordered complex system composed of various mineral constituents. Besides their important physical and chemical properties for engineering applications, their dielectric properties has attracted interest in applying electromagnetic waves to nonintrusive geologic and engineering investigation. Dielectric permittivity reflects the dielectric polarization ability of the materials in response to an applied external electric field. The mechanisms of the dielectric polarization generally fall into the following categories: deformation polarization, dipole orientation polarization and ionic polarization (Nover 2005). The dielectric permittivity of stones is not only a function of frequency of the applied field, but also depends on the mineralogy, porosity and grain geometries as well as the electrochemical interactions between the constituent elements of the stones,

especially in the presence of pore fluids. Thus, the dielectric response in the frequency and time domain is often used for physical and chemical analysis of materials (Iskander *et al.* 1983).
In this work, we focused on the dielectric constant introduced by water (moisture) in the porous stones. Water molecules possess a permanent dipole moment, which tends to rotate towards the direction of the applied electric field. The rotation polarization is frequency and temperature dependent and the polarization relaxation process is associated with the mutual interactions of the dipoles and their attaching matrix. The total dielectric constant of the saturated stones largely depends on the volumetric percentage of the moisture in the stones since water has a much larger dielectric constant than that of the stones.
The dielectric response to an external field generally depends on the frequency of the field, i.e., the response of the polarization to the field is not instantaneous and there is a phase difference, thus, the dielectric permittivity is a complex function of frequency. The relative complex permittivity ε_r consists of two parts as the following:

$$\varepsilon_r(\omega) = \varepsilon_r'(\omega) - j\varepsilon_r''(\omega) \quad (1)$$

where ε_r' is the real part, called the 'dielectric constant'; ε_r'' is the imaginary part, referred to as the 'dielectric loss'. The ratio of the dielectric constant to the dielectric loss is defined as loss tangent, which is mathematically expressed as:

$$Tan\delta = \varepsilon_r''(\omega)/\varepsilon_r'(\omega) \quad (2)$$

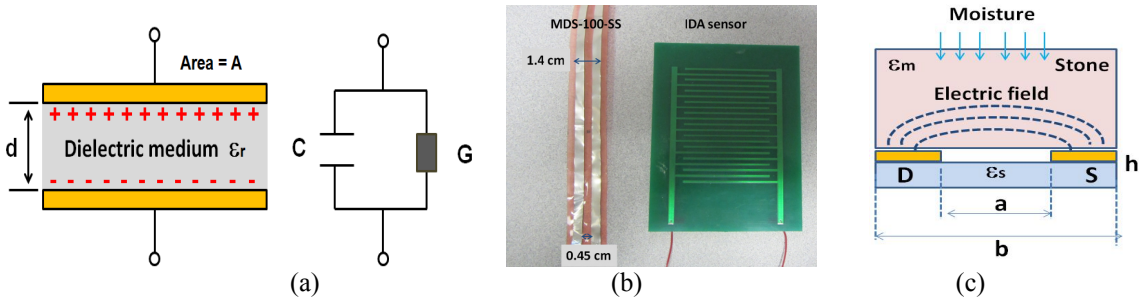
Therefore, study of the dielectric permittivity in the frequency domain provides information on the dielectric properties of the materials of interest. Since the dielectric constant is contributed by all components of the saturated stones, the average dielectric constant can be calculated by properly modeling the complex mixtures of the stones (Martinez *et al.* 2001). As far as the moisture is concerned, the dielectric constant is a function of the volumetric percentage of the moisture content (MC) relative to the materials.

Capacitance Measurement of Dielectric Permittivity

Capacitance measurement is the most commonly used method for determining dielectric permittivity. For example, a capacitor composed of two parallel plates is shown in Figure 1(a), where the dielectric material is filled between two parallel plates. The relationship between capacitance and dielectric constant is expressed in the following mathematical formula:

$$C = \varepsilon_r \varepsilon_0 \frac{A}{d} = \varepsilon_r C_0 \quad (3)$$

Where ε_r is relative dielectric constant of the dielectric medium, ε_0 is the dielectric constant in the vacuum, A is the area of the plate and d is the distance between two plates.



(a) (b) (c)

Figure 1. (a) Two-parallel-plate capacitor with the dielectric medium and its equivalent electrical model; (b) Two types of the planar fringing field capacitors used in this work; (c) Schematic of the sensor electrodes D/S with a substrate of ε_s and a test material of ε_m

In a capacitive electric circuit, admittance is often conveniently used for describing the electric behavior. The admittance, Y, is defined as the inverse of the impedance, Z, i.e., Y = 1/Z. Where Z = R + jX and Y = G + jB, where R is resistance (ohm) and X is reactance (ohm); G is conductance (Siemens) and B is susceptance (Siemens). Since $Y = j\omega\varepsilon_r C_0$, therefore, $B = \omega C_0 \varepsilon_r'$ and $G = \omega C_0 \varepsilon_r''$. It can be seen that G is related to the $\varepsilon_r''(\omega)$, and B is related to the $\varepsilon_r'(\omega)$. Hence, its electrical circuit is equivalently viewed as a pure capacitor C in parallel with a conductor G, as depicted in Figure 1 (a). Based on the electrical circuit theory, the real part and imaginary part of the impedance of the capacitor can be experimentally measured, thus, the dielectric constant $\varepsilon_r'(\omega)$ and its loss $\varepsilon_r''(\omega)$ can be experimentally determined.
In the dielectric materials with the ionic conduction, the measured loss usually includes both the dielectric loss and the conduction loss, i.e., $\varepsilon_r''(\omega)_{eff} = \varepsilon_{rd}'' + \sigma/\varepsilon_0\omega$, where σ is the conductivity (Rusiniak 1998).

For most civil infrastructure materials, $\varepsilon_r'(\omega)$ is highly sensitive to the fraction of water content, and the effective loss $\varepsilon_r''(\omega)_{eff}$ increases significantly via enhanced ionic conduction.

Capacitance Sensing Elements

The measurement of dielectric permittivity by the capacitance method relies on the adequate construction of the capacitor with the materials of interest as the dielectric medium, such as, the two-parallel-plate capacitor in Figure 1 (a), a geometrically well defined capacitor. The choice of the specific geometrical configuration of a capacitor relies on the specific applications and the dielectric materials of interest. For our research, in order to easily implement the capacitance sensors in the masonry wall, planar capacitors with the electrodes of two separated parallel metal conductors and an interdigitated array (IDA) were chosen, as shown in Figure 1 (b). Unlike the two parallel plate capacitor where the electric field is confined in the space between the two plate electrodes, the electric field of the planar capacitor radiates from one electrode to another, called the fringing electric field. In this case, the masonry material acts as the dielectric medium where the planar capacitor is embedded. The cross-section of such a capacitor is schematically shown in Figure 1 (c), where the material on the top of two electrodes has the dielectric constant ε_m which is assumed to be the masonry, and the dielectric material of ε_s is assumed to be the substrate of the sensing electrodes. Their capacitance can be calculated based on the following formula (Dean 2012):

$$C(DS) = \varepsilon_0\left(\frac{\varepsilon_m + \varepsilon_s}{2}\right)k\left(\sqrt{1-\frac{a^2}{b^2}}\right)/k\left(\frac{a}{b}\right) + \varepsilon_0\varepsilon_a\frac{h}{a} \tag{4}$$

Where $k\left(\sqrt{1-\frac{a^2}{b^2}}\right)$ and $k\left(\frac{a}{b}\right)$ are the elliptical integrals.

Using the IDA sensor as an example, the capacitances of the IDA capacitor was calculated. The dimensions of the electrodes was a = 2 mm, b = 4 mm; using general properties of the FR4 print circuit board, the typical thickness of electrodes: h = 35 μm, the dielectric constant of the FR4: ε(s) = 4.35 @ 500 MHz, the average coating thickness (IPC standards) of 0.1mm, and the average dielectric of the coating ε(coating) = 3. For the IDA sensor with the protective coating layer, named as IDA #1, C1=22.1 pF (in air). For the IDA sensor without the protective coating layer, named as IDA#2, C2=20.9 pF (in air). The calculated values are very close to those measured capacitances of 22.3 pF for IDA #1 and 20.5 pF for IDA#2 in air using an Agilent handheld capacitance meter.

Capacitance Measurement Instruments

Many methods can be used to measure capacitance in terms of the measuring conditions and requirements. Selection of measurement techniques depends on the measuring frequency coverage, impedance range, accuracy and ease of operation. The following methods: Auto balancing bridge, I-V technique, RF I-V technique and Network Analyzer are often used, including the Agilent Impedance analyzer based on the balance bridge. Every technique has its own advantages and disadvantages depending on the specific measuring conditions (Agilent 2009).

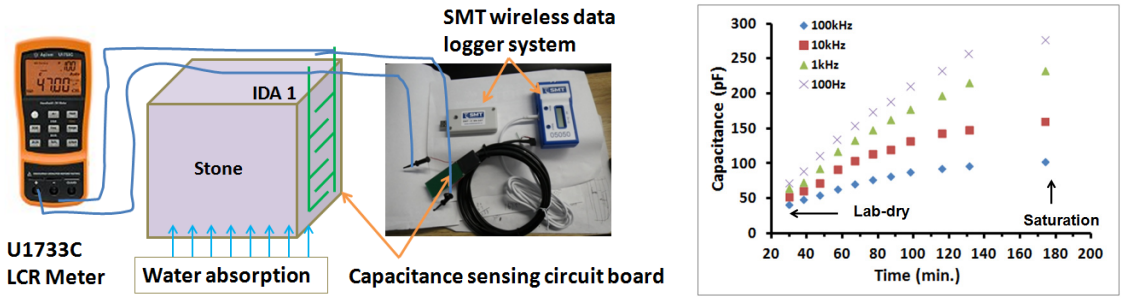
Besides commonly used impedance measurement techniques, capacitance sensing can be done using the charge/discharge mechanism of a capacitor. With highly advanced microelectronics, the integrated on-board capacitance microcontroller makes capacitance sensing very easy. The microcontroller uses the Charge Time Measurement Unit (CTMU) in conjunction with the A/D Converter to measure time and capacitance. The CTMU uses a fixed current source to charge a capacitor. When the amount of charging time is fixed, the voltage across the capacitor is proportional to the charges, and the voltage is read by the A/D converter. The mathematical expression is $I \times t = C \times V$, where I is the fixed current from current source; t is the charging time, C is the capacitance and V is the voltage. The CTMU can create a time delay and generate output pulses independent of the system clock, and the pulse width changes with the external capacitance, providing a way to measure capacitance (Microchip 2011).

The highly developed wireless communication technology makes wireless sensing very promising in the structural health monitoring field (Kim *et al.* 2007; Sidén *et al.* 2007). Structure Monitoring Technology Research Limited (SMT) has developed a wireless data logger system in combination with a microcontroller implemented capacitance sensing circuit as shown in Figure 2 (a). The figure includes the SMT Data Acquisition Unit SMT-A2 and the wireless USB interface (SMT-I2) as well as the capacitance sensing circuit board. Capacitance is measured by the capacitance sensor circuit and digitally converted using the ADC in the SMT-A2. Data is then wirelessly transmitted to a gateway computer and synchronized with a cloud-based server for further processing.

RESULTS AND DISCUSSIONS

Moisture Content Measurement

Moisture content in the masonry stone (Ohio sandstone) was tested as shown in Figure 2 (a) where the IDA capacitance sensor was tightly attached on the surface of the stone and the four side-walls of the stone were wrapped using the moisture insulating tape. The bottom surface of the stone was in contact with water, the absorbed water traveled upward until it reached the top surface of the stone.



(a) (b)

Figure 2. (a) Test setup of the moisture content measurement using the IDA capacitance sensor with the LCR meter and the wireless capacitance sensing system; (b) Capacitance measured at different frequencies using IDA #1 sensor during the moisture saturation

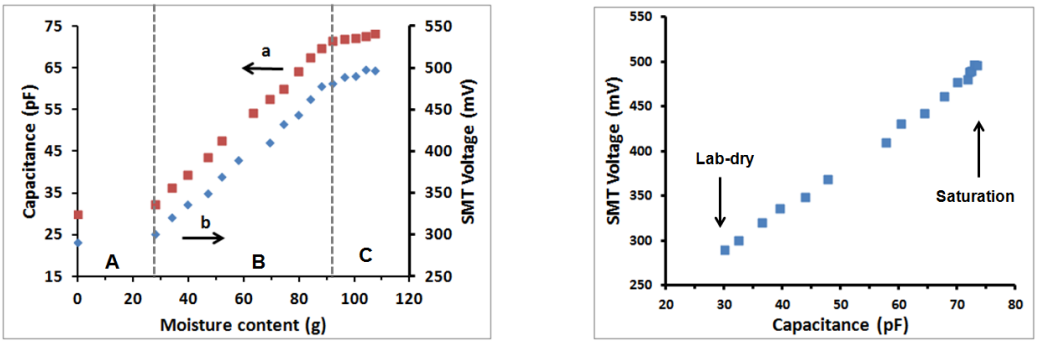
Before saturation of the stone sample, the LCR meter and the SMT wireless sensing system were used to measure the capacitance of the sensor. The measured capacitances for the IDA sensor in air and with the stone in a lab-dry state are shown in Table 1. The capacitances were measured under three different frequencies. The capacitances become larger when the IDA sensor was integrated with the stone. This is attributed to the additional dielectric constant contributed by the stone. The capacitances at three frequencies are very close both for the sensor in air and on the stone in the lab-dry state. It will be seen later in this paper the capacitance under different frequencies can be very different when the stone is moisture saturated. The SMT wireless measurement system gives the output of about 167 mV before the test IDA sensor board was connected to the capacitance sensing board. After the test IDA sensor board was attached on the stone and connected to the capacitance sensing board, the data logger system gives the converted capacitance value of 290 mV.

Table 1. IDA capacitance measured using Agilent LCR Handheld Meter

	IDA sensor in air		IDA sensor with stone (lab-dry)
LCR meter	Frequency	Cp (pF)	Cp (pF)
	@ 1kHz	22.93	31.77
	@ 10 kHz	22.75	31.04
	@100 kHz	22.33	30.18
SMT data Logger			290 mV

The IDA sensor/stone assembly was weighed before it was placed into the water container. After the stone was set in the water of about 1 cm high, a measurement was taken every 10 minutes during the moisture saturating process. Figure 2 (b) shows the measured capacitance at four frequencies during the moisture saturation process. It was observed that the measured capacitance increases with the saturating time. The weight of the instrumented stone was also measured corresponding to the capacitance measurement. Figure 3 shows the data from the wireless measurement system and from the LCR meter where both the measured capacitance and the voltage of the wireless system are plotted against the absorbed moisture weight. As shown in Figure 3 (a), during the moisture saturation, the region A shows very little change of the measured signals for an almost 30 g water increase before the absorbed moisture reached the sensing electrodes. In the region B, for the absorbed moisture content weight ranging from about 30 g to 90 g, both the output of the SMT monitoring system and the capacitance from the LCR meter show a linear increase with the moisture weight. This suggests the moisture travelled through the stone and was detected by the IDA capacitance sensing electrodes. For the weight range larger than about 90 g, since the moisture front already passed over the area of the IDA electrodes, the slow capacitance increase is assumed to be induced by the continued saturation of the stone near the IDA electrodes. In Figure 3 (b), the voltages of the wireless system are plotted against the capacitances measured by the LCR meter, showing a very linear relationship between them. This indicates a good correlation in response to the

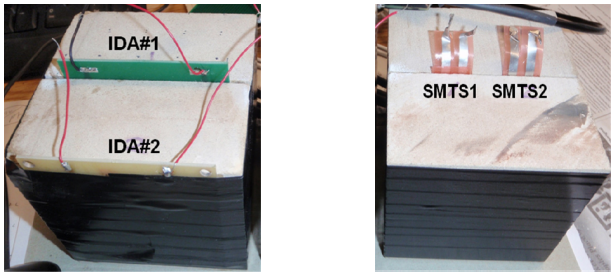
moisture content. The results demonstrate that both instruments are capable of measuring the moisture content in the masonry stone.



(a) (b)

Figure 3. Voltage and capacitance @100 kHz measured using the wireless measurement system and the LCR meter

Effect of the Interface of Capacitance Sensing Electrodes



(a) (b)

Figure 4. Instrumented stone samples with two IDA sensors (a) and two SMT sensors (b)

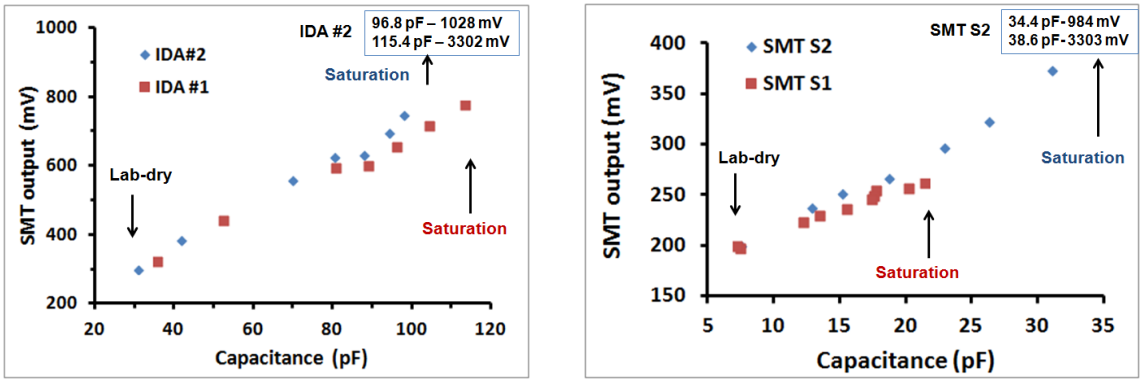
Considering the capacitance sensors are integrated with the masonry stones and are usually embedded inside the masonry walls, not only the durability and reliability of the sensing elements but also whether the electrodes are electrically conducting or electrically non-conducting become important issues. In order to investigate the influence of the interface of the sensing electrodes with the stones on the capacitance measurement, the test work was done using two IDA sensors and two SMT tape sensors as shown in Figure 4 (a), where the IDA #1 has the sensing electrodes covered with a thin protective coating layer and the IDA #2 is same as the IDA #1 but with no the coating layer. The IDA #1 was tightly sandwiched between the two slabs of the stones and the IDA #2 was tightly bonded on one side wall of the stone. Two physically simple and flexible capacitance sensors, named SMT S1 and SMT S2, were used as shown in Figure 4 (b). Both SMT S1 and SMT S2 are made from the two parallel stainless steel electrodes on the plastic tape of about 0.3 mm thick. The difference is the electrodes of SMT S1 are covered using the same plastic tape with the seams of two pieces plastic tapes sealed using the epoxy and the electrodes of SMT S2 are exposed. Thus, the electrodes of SMT S1 are moisture insulated and DC conduction is blocked and the electrodes of SMT S2 are in direct contact with the stone and are DC conducting. The selection of this type of tape sensor is because of its flexibility, robust electrodes and easy integration into the masonry walls. Both the SMT S1 and SMT S2 tape sensors were tightly sandwiched between two slabs of the stones. The side walls of the stone samples were wrapped using moisture insulating tapes such that moisture saturation and the drying is only allowed from the top and bottom sides of the stone.

The instrumented stones were considered moisture saturated when the absorbed moisture permeated upward through the whole stone after the stone was placed in the water. After the instrumented stones were moisture saturated, measurements were taken during the drying period in the lab-dry environment. Table 2 provides the capacitances and voltages measured using the LCR meter and the SMT wireless system for these four sensors under the conditions of the lab-dry state and the moisture saturation state. Figure 5 (a) and Figure 5 (b) show the data measured using the wireless data logger system and the LCR meter. In Figure 5 (a), the measured voltage and capacitance are well correlated for both the IDA #1 and IDA #2 sensors. The values of both sensors are very close for the capacitance variation below 100 pF. The capacitances measured by IDA #1 and IDA #2 do not show much difference, but the voltages measured for the IDA #2 sensor by the SMT wireless system shows a very rapid change near the moisture saturation state, as shown in Figure 5 (a), where the voltage rapidly changed from 1028 mV to 3302 mV corresponding to the capacitance change from 96.8 pF to 115.4 pF. In contrast, the

voltage of the IDA #1 sensor shows an almost linear response up to the moisture saturation state. The results suggest the IDA #1 sensor works for both capacitance measurement instruments in the full moisture range, however, the IDA #2 sensor behaves irregularly near the moisture saturation state.
In Figure 5 (b), for the SMT S1 tape sensor with the moisture insulated electrodes, the voltage of SMT wireless system correlates well with the measured capacitance corresponding to the whole saturation range. The measured capacitance is only about 22 pF in the saturation state. In contrast, the SMT S2 tape sensor shows the measured capacitances are much larger than those from the SMT S1 sensor corresponding to the moisture content when the moisture state is approaching saturation. Similar to the IDA #2 sensor, the measurement for the SMT S2 sensor by the SMT wireless system also shows abnormal behavior near the moisture saturation state. The measured voltage rapidly changes from 984 mV to 3303 mV corresponding to the capacitance change from 34.4 pF to 38.6 pF near saturation.

Table 2. Measured data for a lab-dry state and the moisture saturated state for 4 sensors in Figure 4

	IDA#1		IDA#2		SMT S1		SMT S2	
	Lab-dry	Saturation	Lab-dry	Saturation	Lab-dry	Saturation	Lab-dry	Saturation
Cp (pF)@1kHz	56.85	263.2	52.68	6000	15.19	23.72	16.68	2963
Cp (pF)@10kHz	41.16	216.2	39.67	369.7	9.42	22.58	9.58	126
Cp (pF)@100kHz	35.84	151.8	30.97	115.5	7.35	21.36	7.50	38.6
SMT voltage (mV)	322.1	868.5	298.9	3303	196.7	261.3	197.0	3303



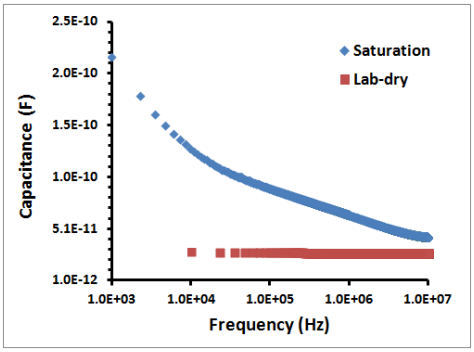
(a) (b)

Figure 5. Measured SMT voltages are plotted against the measured capacitances @100 kHz for the instrumented stones as shown in Figure 4

Comparing the results from the IDA #1 with the 0.1 mm thick moisture insulating layer on the electrodes, the plastic tape of the SMT S1 is about 0.3 mm thick. Thus, the results of the capacitance measurement in the moisture saturation state for the SMT S1 suggests the thick insulating layer may play a major role for the capacitance measurement at the measurement frequency of the LCR meter. As to the measurement abnormality given by the wireless capacitance sensing system near the saturation state for both the IDA #1 and SMT S2 sensors, it can be attributed to the higher electrical conduction of the mixture of the moisture and stone at the measurement frequency. The capacitance measurement based on the charging/discharging of a capacitor no longer works after the conduction reaches a critical point.

Frequency Dependence of Capacitance Sensors

As previously shown in Figure 2 (b), the capacitance measured using the LCR meter at four different frequencies clearly shows the frequency dependent behavior during the moisture saturating process. In the lab-dry state, the measured capacitances are very close at the different frequencies. As the moisture content increases in the stone, the capacitance at the lower frequencies becomes higher than at the higher frequencies. Such a frequency dependent behavior can be attributed to the complicated polarization process in the saturated materials in which the induced interfacial polarization, double layer polarization and ionic conduction significantly affect the capacitance measurement (Nover 2005). Further study on this frequency dependent behavior was conducted by measuring the capacitance and conductance of the sensors using an impedance analyzer, as shown in Figure 6 and Figure 7.



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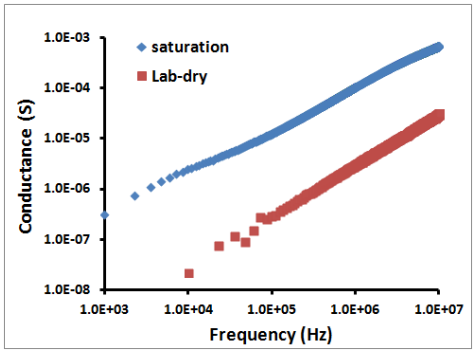
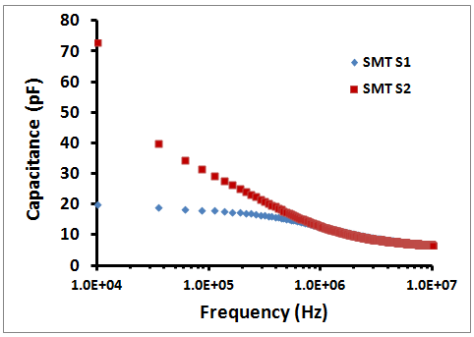
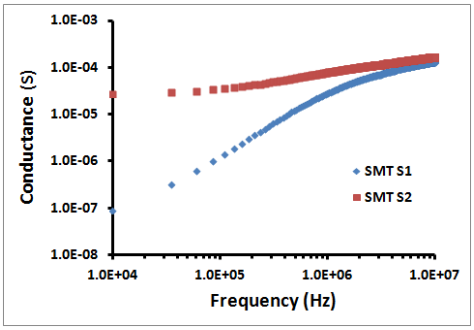


(b)

Figure 6. Capacitance (a) and conductance (b) measured against frequency using the Agilent impedance analyzer under the moisture conditions of the lab-dry and saturated states for the IDA #1 sensor



(a)



(b)

Figure 7. Capacitance (a) and conductance (b) measured against frequency using the Agilent impedance analyzer under the moisture conditions of the lab-dry and saturated states for the SMT S1 sensor and the SMT S2 sensor

Figure 6 shows the capacitance and conductance measured for the IDA #1 sensor by sweeping frequency from 1 kHz to 10 MHz using the Agilent impedance analyzer. It can be seen that the measured capacitances show little change under the lab-dry condition, but show a pronounced change and a strong frequency dependent behavior under the moisture saturation state. The conductance measurement for the lab-dry and the saturation states also show frequency dependent behavior. Figure 7 shows the measured capacitance and conductance for the SMT S1 and SMT S2 sensors when the moisture content is in a near saturation state. The data clearly shows the difference between the two sensors at the lower frequencies. The SMT S1 sensor with the insulated electrodes shows a very small capacitance change at lower frequencies while the SMT S2 sensor with the exposed electrodes show a very large capacitance change at lower frequencies. This is assumed to be caused by the moisture insulating layer and strongly suggests that the thick moisture insulating layer greatly affects the moisture capacitance measurement. The thicker insulating tape for the SMT #1 sensor seems to dominate the capacitance behavior at lower frequencies. At frequencies larger than 1MHz, the capacitance for both the SMT S1 and SMT S2 shows very close values. This suggests the moisture induced polarizations surrounding the electrodes and the interface of the grains in the stone are greatly reduced at higher frequencies. The conductivity measurement, as shown in Figure7 (b), clearly shows the difference between the SMT S1 and SMT S2. The conductivity for the electrodes exposed sensor is much higher than that for the moisture insulated electrodes, especially at lower frequencies. The conductance of the non-insulated SMT S2 sensor shows a high conductance of around 0.019 mS above 10 kHz. As tested for the SMT wireless capacitance sensing system using a circuit with a parallel capacitor C and resistor R, when conductance G > 0.019 mS (where G=1/R), the voltage of the wireless system rapidly increases and reaches the maximum voltage of 3303 mV. This means the very high conductance will affect the measurement of the wireless data logger system, causing the abnormality of the voltage measurement as observed when the stone reached the saturation state. The abnormal behavior of the SMT wireless measuring system may be solved by using a very thin moisture insulated coating layer on the sensing electrodes, as suggested by the conductance measurement for the IDA #1 in Figure 6 (b) where the measured conductance is smaller than 0.01 mS.

Therefore, a better understanding of how the measuring frequency and the insulating/non-insulating electrodes affect the capacitance and conductance is important for constructing moisture measurement instruments, especially instruments for measuring the moisture content in masonry materials.

CONCLUSIONS

This paper has presented the investigation on how to apply the dielectric based capacitance measurement for moisture content monitoring in masonry stones. The two types of planar capacitors with the fringing electric field have been tested using the commercially available LCR capacitance meter and the wireless capacitance sensing system. The measured capacitances and voltages demonstrate that the capacitance sensors and both instruments are capable of moisture measurement in the masonry stones. The dielectric permittivity determined through the capacitance measurement is frequency dependent. The conductance of the moisture within the stones affects the capacitance measurement, especially the measurement near the moisture saturation state when using the wireless capacitance sensing system. The tests of the moisture-insulated and non-moisture-insulated electrodes of the capacitance sensors indicate their influence on the capacitance measurement in relation to the moisture content. The test results suggest that the fringing field capacitors with a very thin moisture insulating coating on the electrodes give a well correlated relationship between the capacitance and the moisture content when the LCR meter and the wireless sensing system are employed as measurement instruments. The frequency dependence of the capacitance in the stones suggests that a higher measuring frequency should be used in order to reduce capacitance induced by the interface and double layer polarization processes. The test results have led us to construct a capacitance sensing circuit with a frequency of 5 MHz for measuring moisture content in the masonry stone walls. This work proves that the dielectric based capacitance sensors can be used for the moisture content monitoring in the masonry stones using inexpensive commercially available measurement instruments. In particular, the wireless data logger system has good potential for structural health monitoring applications for moisture content monitoring of heritage structures.

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