The 10th International Conference of the Slovenian Society for Non-Destructive Testing
»Application of Contemporary Non-Destructive Testing in Engineering«
September 1-3, 2009, Ljubljana, Slovenia, 431-436

PERMITTIVITY VARIATIONS ON MARBLE BEAMS SUBJECTED TO VARIOUS LOADING LEVELS

I. Stavrakas[1], C. Anastasiadis[1], S. Maurigiannakis[2], D. Triantis[1], Z. Agioutantis[2]

[1] Laboratory of Electric Properties of Materials, Department of Electronics, Technological Educational Institution of Athens, Greece, 12210, ilias@ee.teiath.gr.

[2] Department of Mineral Resources Engineering, Technical University of Crete, Greece

ABSTRACT

Marble beams were subjected to gradually increasing three-point bending from low loading levels up to levels that significant damage was observed. After each loading step the permittivity was measured at three characteristic locations: the tensional, middle and compressional zone of each sample. The permittivity measurements were conducted in the frequency range from 1kHz to 1MHz. The permittivity values were compared for the three locations at the frequency of 10kHz. The experimental results indicate that the permittivity values decrease after each loading at the three selected locations. More specifically, the permittivity variation is more intense at the tensional zone (due to intense cracking processes) than the compressional zone, while the middle zone exhibits the lowest variation in permittivity. Thus, the damage magnitude of each sample can be estimated by permittivity measurements before the fracture of the sample.

Key words: Permittivity, marble, bending loading, damage, Non-destructive testing.

1. Introduction

The application of mechanical loading on a geomaterial influences its mechanical and electrical behaviour resulting in a significant variation of measurable macroscopic quantities. More specifically, the electric properties of geomaterials are greatly affected by micro-damage developed in the bulk of the material due to externally applied mechanical loads. The dependence of the electric properties on mechanical stress has been reported based on Dielectric Spectroscopy experiments in the frequency domain [1,2] and Isothermal Depolarization Currents [3] experiments. It is now clear that the electric properties can be used as potential indices of the magnitude of damage caused by externally applied loads.

Dielectric properties are related with the capability of a material to be polarised under the influence of an electric field. The polarisability of a material depends on its structure and molecular properties and therefore dielectric measurements can provide information in this respect. Dielectric Spectroscopy is a technique that has been used to characterize the rock microstructure and to provide useful information about the relationships governing microstructure, electrical properties, and chemical processes during hydration [4-7]. Complex relative permittivity ε^* (hereafter, referred to as complex permittivity for convenience) is defined as:

$$\varepsilon^* = \varepsilon' - j\varepsilon'' = \varepsilon' + \frac{\sigma}{j\varepsilon_0\omega} \tag{1}$$

where ε' and ε'' are the real and imaginary parts of ε^* respectively, σ is electric conductivity, ε_0 is vacuum permittivity, ω is the angular frequency ($\omega = 2\pi f$) and $j = \sqrt{-1}$.

The real part of the complex permittivity is a measure of the amount of energy from the electric field stored in the material and can be calculated by the measured capacitance (C) in the studied frequency using the formula:

$$\varepsilon' = \frac{4tC}{\varepsilon_0 \pi d^2} \tag{2}$$

where t is the sample thickness, d is the diameter of the electrodes, $\varepsilon_0 = 8.856x10^{-14}\ F \cdot cm$ is the permittivity of free space. The imaginary part of the complex permittivity is a measure of how dissipative or lossy the matter is, in relation to the electric field.

In this work, marble beam samples were subjected to three point bending at various loading levels. After each loading the spectrum of the permittivity was plotted for three characteristic locations of the sample with respect to the application of load, the tensional, the middle and the compressional zones. The permittivity measurements were conducted in the frequency range from 1kHz to 1MHz. A characteristic frequency was selected and the behaviour of the permittivity was compared for the three characteristic locations. The experimental results show clearly that the permittivity values are significantly affected at the location where most of the damages take place.

2. Materials and Experimental Techniques

2.1 Materials

To conduct the experimental procedure marble samples collected Mt. Penteli were used. Marble belongs to the class of metamorphic rocks. It contains structural inhomogeneities due to their formation or due to external causes. The specific type of marble is mainly composed of calcite (98%). Other minerals also contribute to the marble composition like muscovite, sericite and chlorite. Its porosity is approximately 0.4% and can be characterised as high regarding the influence it can have on the permittivity spectrum. Moreover, the water content of marble as well as the environmental humidity that can penetrate the sample can significantly affect the permittivity spectrum. Since the captured water in the pores affects the interfacial capacitance and consequently the total capacitance of the sample this parameter must be obligatorily controlled. Thus, the complete experimental procedure took place in a controlled environment for both temperature and humidity conditions. Matrix rocks of the above origin were intentionally selected to be quasi single grained.

The dimensions of the prismatic samples subjected to bending were 100mm long and 26mmx10mm in cross section. In order to achieve acceptably dry material, the samples were heated for twenty four hours in a chamber of constant 105°C temperature.

2.2 The Experimental Techniques

A series of three point bending (3PB) tests was carried out with prismatic samples 100mm long and 26mmx10mm in cross section (see Fig. 1). The tests were conducted with a 3PB test system mounted on Tri - Scan 50kN loading frame. The samples were placed on two steel rollers at a distance of 80mm from each other. The load was applied on the middle of the upper surface of the beam. In typical testing procedures, the load on the sample is applied continuously at a displacement rate of 0.06mm/sec as recommended by Standard Test Methods (ASTM). The lower zone area of each sample (area: -1, see Fig. 2) was subjected to tensile stress, while the upper zone area (area: +1, see Fig. 2) was compressed. Between the upper and the lower zones there is a layer which is called the natural zone (area: 0, see Fig.1). The length of this natural layer of the beam does not change. The first five sample beams were used to specify the mean strength of the samples which was found to be approximately 0.97kN. Bending loads ℓ were applied successively on the samples at 0.4kN and 0.5kN intervals?. Between each load application dielectric measurements were conducted, on both saturated and dry samples, at the three predefined areas (+1, 0, -1).

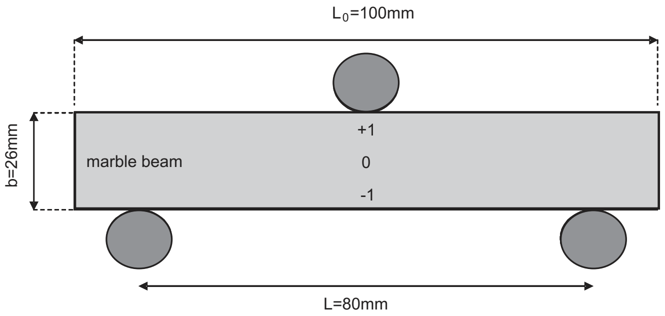

Fig. 1: Testing configuration for the 3PB tests

Sample mounting is shown in Figure 1. The dielectric measurements were conducted using an LCR meter (Agilent model 4284A), accompanied by the dielectric test fixture (Agilent model 16451B) and further supported by a computer for data recording, storage and analysis. The dielectric test fixture that was used to hold the specimen was protected by a cabin providing constant temperature (298K), inert atmosphere by continuous effusion of inert gas and also low humidity. For all dielectric measurements, the amplitude of a sinusoidal ac voltage source was kept constant at 2V.

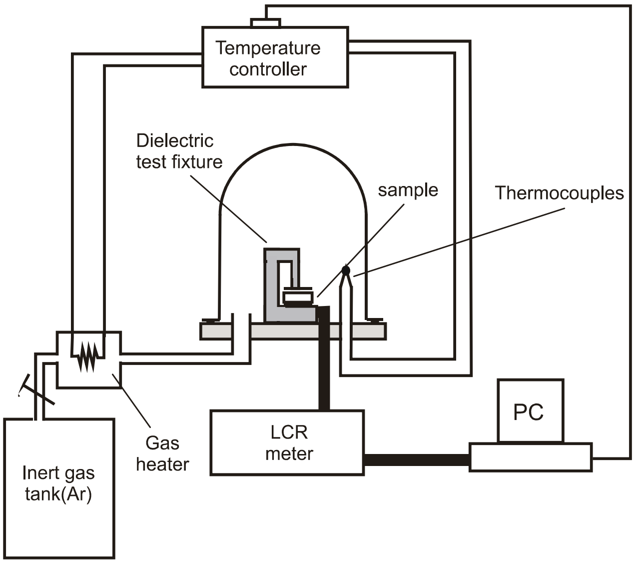

Fig. 2: Schematic of the permittivity measuring system

It is important to mention that the marble used in the experiments is characterised by its low porosity, which is a necessary condition, especially when dealing with dried samples as the permittivity mechanisms highly depend on the water content of the sample.

3. Results and Discussion

Figure 3 shows the permittivity spectra in the frequency range from 1kHz up to 1MHz of the used samples for both the dry and saturated conditions when the samples have not suffered any external load. From these results it is clear that the permittivity values are significantly affected by the water content. At the same time the externally applied load creates voids in the bulk of the sample which increase with increasing load. Therefore, it was decided to conduct all subsequent experimental procedures under dry conditions.

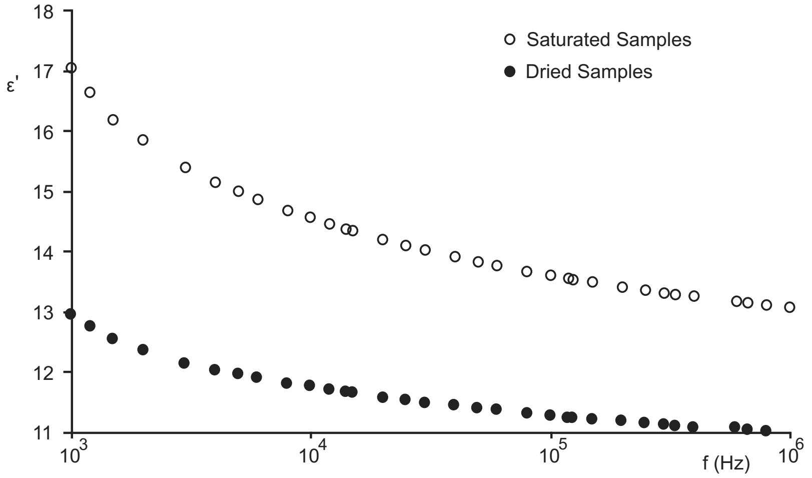

Fig. 3: The permittivity spectra in the frequency range from 1kHz up to 1MHz for unloaded dry and saturated marble samples.

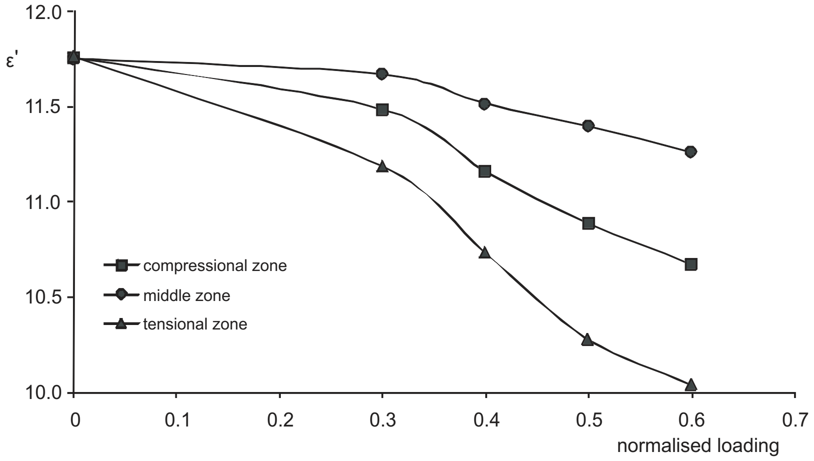

Fig. 4: The behaviour of permittivity with respect to the applied loading. The three curves correspond to the compressional, middle and tensional zone of the sample during each loading.

Consequently, load was applied on the samples forcing them to bend (h prohgoumenh protasi den ennoeitai?). The loading levels were gradually increased from very low values up to 60% of the ultimate bending strength of the sample. The permittivity values at the frequency of 10kHz were compared for the three studied locations (i.e. compressional, middle and tensional zone). The frequency of 10kHz was selected for the analysis, since it was observed to be significantly affected by the loading procedure with respect to the corresponding behaviour of the rest of the spectrum. Figure 4 shows the behaviour of permittivity with respect to the applied load.

It becomes clear that the zones that suffer significant damage due to the applied load show higher permittivity dispersion. More specifically, according to the mechanical models [8-10] there is a high concentration of damage at the lower region (tensional zone) of the beam with respect to the applied load, since brittle materials have very low tensile strength. It is therefore expected that results for this zone will show a higher permittivity dispersion as the applied load increases. The upper part of the beam (compressional zone) that suffers the maximum compressional loading shows a lower permittivity dispersion than the tensional zone, but higher than that of the middle zone that experiences a very low stress regime during the experimental procedure. Observing Figure 4, it becomes obvious that the permittivity variation at the middle zone is very low and this is in accordance to the mechanical damage created in this zone.

4. Conclusions

The presented experimental results manifest that mechanical loading during Three Point Bending tests causes significant variations to the permittivity of rocks and specifically marble.
The real part of the complex permittivity is significantly affected by the applied load. More specifically, the experimental results manifest that the permittivity values show larger variation at the tensional zone, where the damage with respect to the applied load is more extensive and a smaller variation at the middle zone where the applied mechanical moment and the corresponding damage is significantly smaller. This makes the study of permittivity a potential tool of detecting the damage index of a brittle geomaterial using the electric properties of the samples. Consequently this experimental methodology constitutes a valuable non-destructive testing method.

5. References

[1] Triantis D., Anastasiadis C., Stavrakas I., Vallianatos F. Dielectric characteristics of marble rocks after the application of various stress modes before fracture. WSEAS Transactions on Systems. 2004; 3: 102-106.

[2] Anastasiadis C., Stavrakas I., Kyriazopoulos A., Ninos D., Triantis D. Non destructive damage estimation on rocks with laboratory measurements of dielectric loss (tanδ). Proceedings of the 8th International Conference of the Slovenian Society for Non-Destructive Testing, Portorož, Slovenia, 1-3 September 2005; pp: 401-407.

[3] Stavrakas I., Triantis D., Anastasiadis C.: The influence of externally applied uniaxial stress on Isothermal Depolarization Current mechanisms in rock samples. Journal of Material Science. 2005; 40: 4593–4596.

[4] Jonscher A.K. Dielectric Relaxation in Solids. Chelsea Dielectric; 1983.

[5] Dyre J. Some remarks on ac conduction in disordered solids. Journal of Non-Crystalline Solids. 1991; 135: 219-226.

[6] Chelidze T.L., Gueguen Y., Ruffet C. Electrical spectroscopy of porous rocks: a review- II. Experimental results and interpretation. Geophys. J. Int. 1999; 137: 16-34.

[7] Chelidze T.L., Gueguen Y. Electrical spectroscopy of porous rocks: a review- I. Theoretical model, Geophys. J. Int. 1999; 137: 1-15.

[8] Landis E. N., Shah S.P. Recovery of Microcrack Parameters in Mortar Using Quantitative Acoustic Emission. Journal of Nondestructive Evaluation. 1993; 12: 219-232.

[9] Diederichs M.S., Kaiser P.K., Eberhardt E. Damage initiation and propagation in hard rock during tunnelling and the influence of near-face stress rotation. International Journal of Rock Mechanics & Mining Sciences. 2004; 41: 785–812

[10] Griffith A.A. The Theory of Rupture. In Bienzeno CB, Burgers J.M. (eds). Proceedings of the First International Congress for Applied Mechanics. Delft, Holland, Waltman.1924; 55-63.