Comments and Remarks on the recordings of Pressure Stimulated Currents (PSC), in marble samples in the range of microcracking.

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Abstract: - The results of Pressure Stimulated Currents systematic recordings, in dielectric solids like marbles are presented. The stimulus of such currents was a fast, step-like, increase of uniaxial stress on the samples. Results are extracted and discussion is made on the mode of PSC emissions, the duration of the emission and the correlation of PSC to the damage variable that quantifies the deviation from linearity on stress-strain characteristic curve.

Key-Words: - Pressure Stimulated Currents, PSC, marble, damage.

1 Introduction

The material fracture phenomena, particularly those concerning inhomogeneous materials, such as geomaterials, in association with transient electric phenomena, attract the interest of the scientific community. An additional reason is that such phenomena are promising candidates of earthquake precursors. During the development of the geomaterial deformation, there appear mechanisms of generation of electric signal emission and a number of researchers acknowledge such mechanisms as related to crack generation and propagation in the Earth's crust [1-4]. Although important similarities exist between the fracture of a pristine rock and an earthquake rupture, there are also important differences [5].

In order to understand the mechanisms that produce these electric signals, a number of laboratory experiments of mechanical stress up to sample fracture have been conducted on minerals and rocks (dry and saturated) [6-11]. Furthermore, there are numerous studies and recordings of acoustic emissions due to microcrack opening in rocks and other materials during mechanical stress application [12]. Kaiser effect is also under investigation in order to study materials' behavior when it is subjected to cyclic loading / unloading [13-15].

Recent laboratory experiments conducted on Penteli marble samples have confirmed that the application of a uniaxial stress on geomaterial samples is accompanied by the production of weak electric currents (Pressure Stimulated Currents-PSC) [16-19]. The above experimental procedure is described by the term PSC technique and after the most recent experiments, consists of recording of the currents emitted by geomaterial samples when subjected to either an abrupt stress increase or a monotonically increasing stress up to fracture.

In this paper we will consider in detail PSC recordings that occur during the application of abrupt uniaxial stress increase on marble samples and particularly in the range where the material shows a deviation from linear elasticity in terms of mechanical behaviour, and microcracking is occurring. In this range, the material appears damaged and there is irreversible deformation. Such microcracks weaken the material and result in PSC emissions.

2 Theoretical concepts

The stress S on the material is given as a function of the strain ε. For the linear elasticity range it can be stated that:

$$S = Y_0 \cdot \varepsilon \tag{1}$$

where Y_0 is the Young's modulus of the undamaged material which is constant in the elastic range. When the stress takes values that lead further than the (linear) elastic region then microcracks occur. For a prescribed stress S, the strain ε is greater than the value given by Eq. 1. Accordingly, we write [5]:

$$S = Y_{eff} \cdot \varepsilon \tag{2}$$

where Y_{eff} is the effective Young's modulus and it is no longer considered as constant. In the plastic range the Young's modulus becomes progressively smaller while stress increases. A continuum approach to this process is to introduce a damage variable a so that [20,21]

$$Y_{eff} = Y_0(1 - D) \qquad (3)$$

The damage variable D quantifies the deviation from linear elasticity and the distribution of microcracks. In general 0<D<1. When D=0, linear elasticity is obtained with Eq. 1 valid, but when D=1, failure occurs. The damage variable is depended only on the applied stress D(S).

In the experiments to be described, the macroscopic parameter that creates the PSC is the variation rate of the uniaxial stress (dS/dt). It has been observed that the above rate affects the magnitude of the PSC peak, whereas the determination of its value is significantly affected by the area of application of the abrupt step stress increase (linear elasticity region or damage region) [17,18]. The correlation of the PSC peak magnitude with the uniaxial stress rate variation can be described by a scaling factor as follows:

$$\Gamma = \frac{I_{max}}{<dS/dt>} \qquad (3)$$

where I_{max} is the maximum value of the emitted PSC during the application of a uniaxial stress step and <dS/dt> is the corresponding average stress rate of the step. In case that dS/dt remains constant during all stress steps factor Γ is proportional to the I_{max} value.

Alternatively, by introducing the normalised stress $(s = S/S_{max})$, where S_{max} is the maximum recorded strength of the material before fracture; we define a corresponding scaling factor as follows:

$$\gamma = \frac{I_{max}}{<ds/dt>} \qquad (4)$$

Another important parameter that will be considered at this paper is the duration t_e of the total PSC emission time after the commencement and completion of the uniaxial stress step application.

3 Sample characteristics and experimental description

In the described experiment, Dionysos marbles collected from Mt. Penteli, Attica were used. The Dionysos marble is mainly composed of calcite (98%) and other minerals, such as muscovite, sericite and chlorite. Its content in quartz is very low, about 0.2%. Its density is 2.7 g/cm^3 and its porosity is approximately 0.4%. The geometric characteristics of the prismatic samples were 69.6mmx49.0mmx51.2mm. The average fracture limit of the samples was measured to be in the range from 50MPa to 60MPa.

The stressing system comprised a uniaxial hydraulic load machine (Enerpac–RC106) that applied compressional stress to the sample. For conducting the electrical measurements of PSC recordings, a sensitive programmable electrometer Keithley 617 was used, (current range from 0.1 fA to 20 mA). The experimental setup of the applied technique as well as the procedure of PSC recording has been described in previous works [16,18].

The stress-strain curve of the marble samples shows that when the normalized stress s exceeds the limit of 0.7 the material has practically abandoned the (linear) elastic region where the Young's modulus becomes progressively smaller when stress increases [19].

4 Experimental results and discussion

Initially, the marble rock sample was subjected to three uniaxial stress steps which correspond to a range of normalized stress from 0.51 to 0.76. Fig. 1 shows the three uniaxial stress steps with respect to time and the corresponding PSC recordings during the uniaxial stress increase, as well as while the uniaxial stress was kept at the high stress level. The stress is maintained on the sample with the high stress level lasting at least for the time needed for the PSC to be restored to the minimum level (background current).

The first uniaxial stress step that was applied corresponds to a level of normalized stress of 0.51<s<0.62. This range belongs to the materials linear part of mechanical behaviour. The rise time t_r of the uniaxial stress, from the low to the high stress level was 4s. The average normalised stress rate of this stress step was 0.0281s^{-1} and the recorded PSC peak maximum reading was I_{max}=0.15pA. The emission time t_e of PSC until it relaxed at the background level was 28s and is considerably longer than the duration t_r of the uniaxial stress step.

Afterwards, another two uniaxial stress steps were applied (see Fig.1), and their characteristics are described in table 1. In the same table there are included the characteristics of the recorded PSC , as

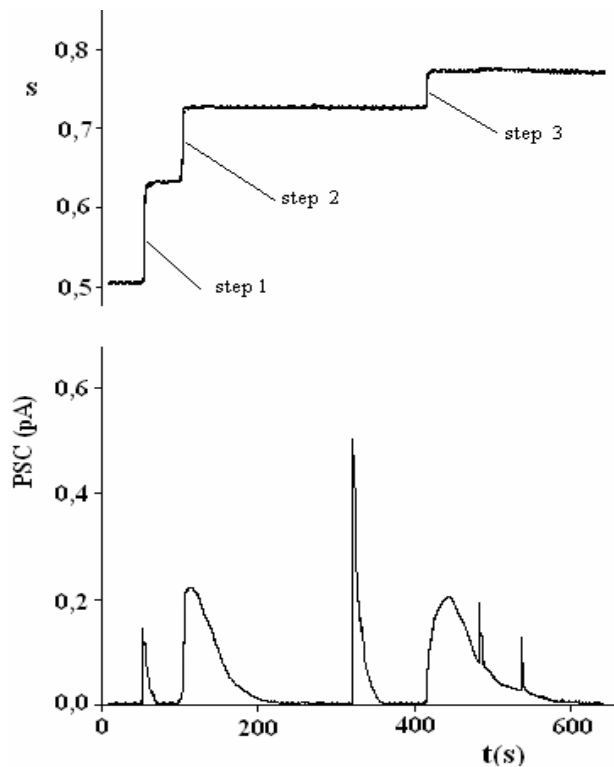well as the accruing value of the scaling factor γ, according to Eq. 4.

Fig. 1: Three uniaxial stress steps and the corresponding PSC recordings with respect to time, in the range 0.51<s<0.76.

The calculation error of the average stress rate of each step <dS/dt> for the conducted experiments is estimated to be around 5% to 7%. Consequently, the error of the γ factor calculation cannot be greater than 10% since PSC recording error is lower than 1%. Table 1 also includes the calculated error of γ factor estimation.

Table 1. Characteristics of the stress steps and the PSC peaks of Fig.1

	1º step stress	2º step stress	3º step stress
Normalised stress range	0.51-0.62	0.62-0.72	0.73-0.76
Time t_r (s)	5.0	5.1	4.0
$<ds/dt>$ (s^{-1})	0.022	0.020	0.008
$I_{max}(pA)$	0.15	0.26	0.20
Time t_e (s)	28	120	190
$\gamma(pC)$ factor	6.8±0.7	13.3±0.9	27±2

Following to the completion of the recording of the PSC emitted during the third stress step, the stress on the sample was decreased, to a value, of normalized uniaxial stress level, s=0.64. From this level, three consecutive uniaxial stress steps were applied, until the final value of the normalized stress level reached s= 0.94. Fig. 2 shows the above three uniaxial stress steps and the corresponding PSC recordings.

The characteristic of the fourth stress step ($0.64 < s < 0.76$), is that the maximum value of the emitted PSC is very low. This fact confirms the "memory effect" in PSC emissions, given that the high stress level of the fourth stress step does not exceed the initial high stress level of the third stress step, prior to the partial discharge of the sample. That is to say that, during the application of the fourth stress step, the new damages occurring are very few, resulting in a mild PSC development.
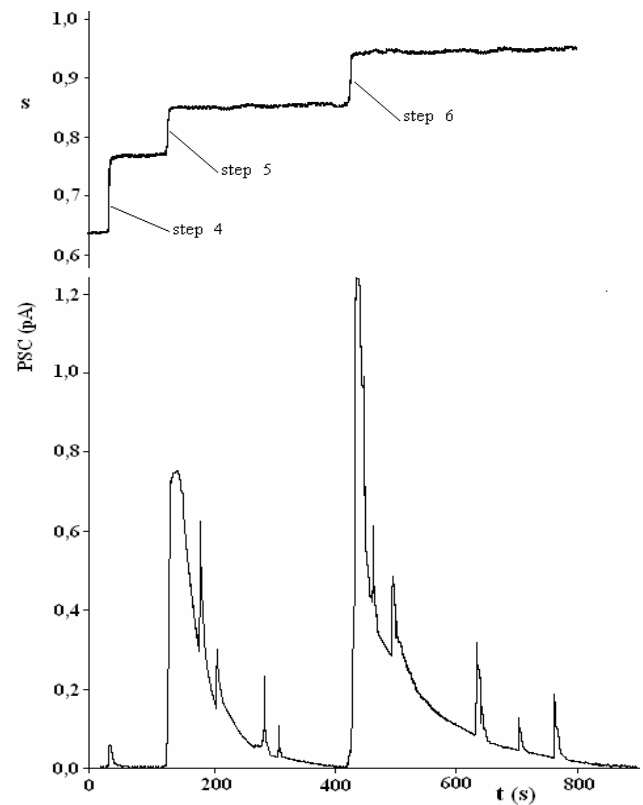

Fig.2: Three new uniaxial stress steps and the corresponding recordings of the PSCs to the normalized stress values of 0.94

An interesting remark which has not been discussed so far is that during the time of the completion of the second stress step and while the applied uniaxial step maintained a stable normalized value (s=0.72), a short and intense current peak was recorded, after the PSC was restored to the value of background current. Further, similar current peaks were recorded during the relaxation of the PSC at the third stress step, as well as the fifth and

sixth stress steps. The above current peaks are attributed to an increase of new microcracks generation, given that the applied uniaxial stress steps (s>0.7) correspond to the mechanical range of the material where damage processes have commenced. It should be noted that the damage processes follow a random pattern of development when the mechanical stress of the sample is in levels where microcracks occur in the material. The above supports the following statement: Following to every microcrack generation process occurring at the time, t_o, there should appear a current peak of random amplitude i_0 and of a random but short duration δt (see Fig.3).

Table 2. Characteristics of the stress steps and the PSC peaks of Fig.1.

	5° step stress	6° step stress
Normalised stress range	0.76-0.85	0.84-0.94
Time t_r (s)	6	11
$<ds/dt>$ (s^{-1})	0.015	0.009
$I_{max}(pA)$	0.75	1.25
Time t_e (s)	280	420
$\gamma(pC)$ factor	50±4	137±10

Consequently, the PSC recordings that have already been presented in Fig. 1 and Fig. 2 are a sequence of such current peaks. In other words the PSC with respect to time I(t) , after the application of a uniaxial stress step can be expressed as :

$$I(t) = \sum_{k=1}^{N} i_k(t) \qquad (5)$$
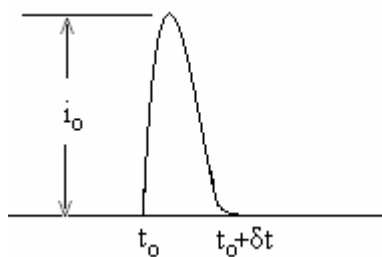
where N stands for the number of microcracks.

Fig. 3. A possible form of peak current when a microcrack is created under a procedure of applied stress.

Another interesting observation is the following: The higher the levels of the uniaxial normalized stress value, after the application of a uniaxial stress step, the longer the PSC emission time is. This is due to the large number of microcracks that

appear, so according to Eq. 5, the relaxation time of the PSC extends more, since the total current I(t) includes more terms. Fig. 4 which demonstrates graphically the emission time t_e of the various PSC with respect to the high value s_h of the normalized stress of each stress step, supports the above. According to Fig. 4, there exists a satisfactory linear relationship.
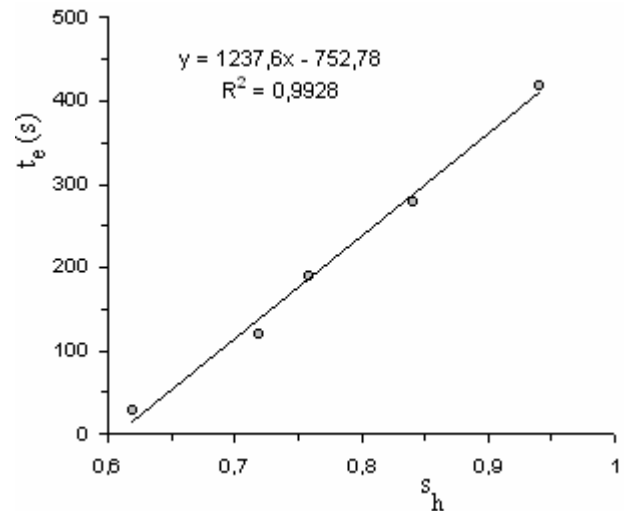

Fig. 4 The values of the emission time of PSC (bold circles) with respect to the level s_h for each uniaxial stress step. The continuous line is the linear fitting.

Finally, an attempt will be made to correlate the scaling factor γ and the damage variable D that quantifies the deviation from linear elasticity of the sample. The calculation of the damage variable can be done by using Eq. 3 and the characteristics of the marble stress-strain curve.
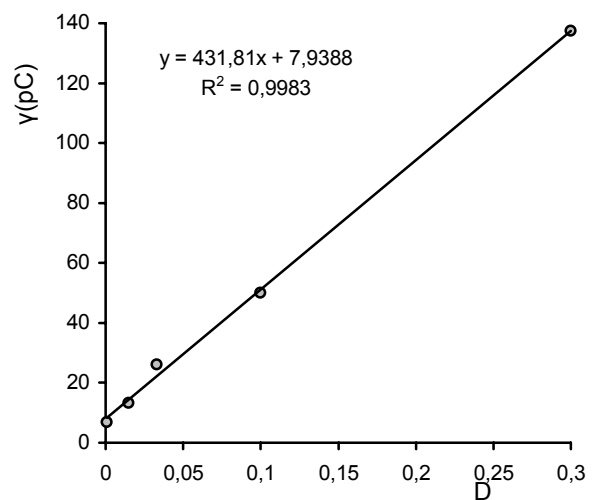

Fig 5. The values of scaling factor γ with respect to the damage variable D. The best fitted line is also presented.

Calculations show that for the used samples the damage variable becomes greater than zero, $D \geq 0$, when the normalized stress reaches values greater than 0.7 $(s \geq 0.7)$. When the normalized stress becomes greater than 0.7 the damage variable continuously increases and for s s=0.94 is 0.3 approximately ($D \approx 0.3$).

Fig. 5 depicts the dependence of the scaling factor γ to the damage variable D. A clear linear relationship is evident between the γ and D constitutes the most important experimental outcome of this work.

5 Concluding remarks

The main conclusions of this work can be summarized in the following four points.

1. Any external stimulation originated by fast stress increase (i.e. stress step) on rock sample leads to PSC emission. The time recording of PSC shows a peak during the completion of the applied stress step. After the peak, the PSC relaxes slowly to the background noise level. This relaxation process takes place while the stress is maintained to the higher stress level of each step.

2. Intensive and short PSC emissions are recorded even in cases that stress is maintained constant but at such levels that damage processes have already been established in the sample.

3. The total emission time of the PSC (i.e. including the relaxation to the background noise level) is proportional to the higher stress value maintained after each stress step applied on the sample.

4. An obvious proportionality seems to characterize the scaling factor γ that correlates each PSC peak with the corresponding normalised stress rate, to the damage variable, D, that quantifies the deviation from linear elasticity of the sample.

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