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Mechanoelectric effects in rocks

Khairullo Makhmudov[1, 2], Zafar Abdurakhmanov[3]

[1]Physical and Mathematical Sciences Laboratory of Strength Physics, Ioffe Institute, 194021 St. Petersburg, 26 Polytekhnicheskaya, Russia
[2]Department of Plant Safety, National Mineral Resources University, 199106 St. Petersburg, V. O., 21-st Linia
[3]Khojend State University, Tajikistan

Email address
h.machmoudov@mail.ioffe.ru (K. Makhmudov), zafar@mail.ru (Z. Abdurakhmanov)

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Abstract
Mechanoelectric effects occurring at elastic mechanical loading of rock samples in neutral medium and at weak electric polarization of the samples have been studied. It has been found that application of weak electric fields to the samples intensifies or weakens the mechanoelectric effects, depending on the direction of the applied field.

1. Introduction

Besides being of purely scientific interest, the mechanoelectric phenomena in naturally occurring dielectrics are of great practical importance because of the problem of interpreting electromagnetic precursors of dynamic manifestations of earthquakes [1-3]. In addition, they facilitate understanding the physical nature of powerful responses to weak causes (including electromagnetic responses to seismic events [4]) and a special state of solids [5,6]. It has been demonstrated that the phenomenon of an electric field arising in dielectric solids under load has a lot in common with the polarization of materials in a weak electric field [7]. Pilot studies of this subject have been published in the 70ties [8,9]. Comprehensive review of the data on the mechanoelectric phenomena in rocks can be found elsewhere [10-19]. In the present work we investigate the effect of mechanical stress on the polarization of dielectric solids in weak electric fields.

2. Experimental

In the present paper we report experimental results obtained for quartz and marble samples. Marble is widely used in laboratory studies since it has all the main properties of dielectric solids but does not exhibit the piezoelectric effect, a property important for understanding the nature of mechanoelectric effects. In what follows, we will call the electric potential arising under mechanical stress the mechanoelectric potential (MEP) to be distinguished from the electric potential (EP) arising due to usual polarization by an electric field. The experimental setup is presented in Fig. 1.

Marble sample, a 40x40x100 mm prism, was loaded by uniaxial compressive stress produced by hydraulic press through glass ceramic insulators. Two electrodes *2* made of a silver powder mixed with epoxy were attached to opposite surface sides of the sample. The electric voltage between the electrodes was supplied by a dc power source. The electrodes can be grounded, if need be. The distribution of electric potentials in the sample is measured with a specially designed electrometer (EM) in a contactless mode. Electrometer probe *3* was attached to a micrometer feed system permitting the scanning along the sample surface maintaining a 2-mm clearance between the probe and the surface. Under uniaxial compressive loading, an induced electric field (IEF) arises in a marble sample, with the side surface taking a positive potential. Without a mechanical load, the sample is polarized if a voltage is applied to the electrodes. In the latter case, the induced electric field is symmetric relative to the sample center and there are parts of the sample surface with positive and negative potentials.

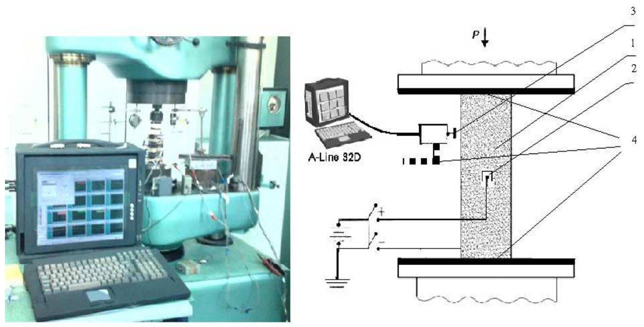

Fig. 1. *Experimental setup including sample (1), electrodes (2), electrometer probe (3) and insulator protecting the probe from electric fields (4).*

A sequence of measurements of IEF performed with fixed probe position is presented in Fig. 2.

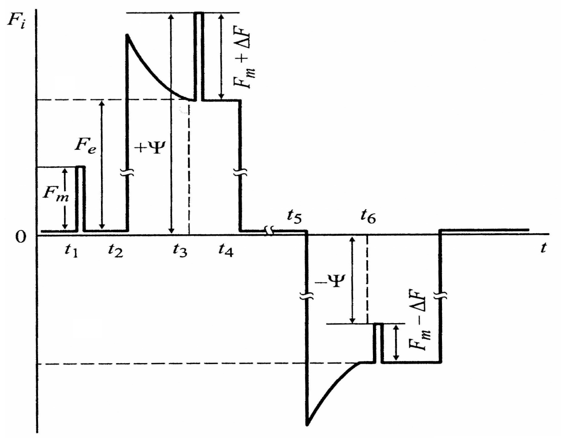

Fig. 2. *The sequence of variations in the electric and mechanoelectric potentials under the actionof mechanical and electric fields applied to the sample.*

At time t_1 the sample was subjected to a uniaxial compressive load P equal to 0.3 of the failure load, and the load was immediately released. A positive induced potential F_e was detected. Next, at time t_2, a positive voltage (of the same polarity as under a mechanical load) was applied to the electrodes. When the electric potential reached the steady state in the period t_2–t_3, the sample was subjected to the same mechanical load again and then was again released. This time, the IEF increased by ΔF. Let us denote the total potential at this moment as $+\Psi$. The induced potential returned to F_m when the mechanical load was removed. Then, at time t_4, the voltage on the electrodes was switched off and they were grounded for some period of time. After that, at the moment t_5, a voltage of the same magnitude but of opposite sign was applied to the electrodes again. The probe detected a negative potential, which soon reached a constant level F_m. Next, at time t_6, the sample was subjected to the same compressive uniaxial load. The detected potential decreased by ΔF, and the total electric potential was equal to $-\Psi$. After the load was removed, the potential returned to F_m. Then, electrodes were grounded to ensure electric neutrality of the sample.

This procedure was repeated in one case with step like increasing mechanical load but with the voltage between the electrodes kept constant. In another case, the voltage was varied but the mechanical load was kept constant. The induced potential F_m increased or decreased depending on the direction of electric polarization of the sample.

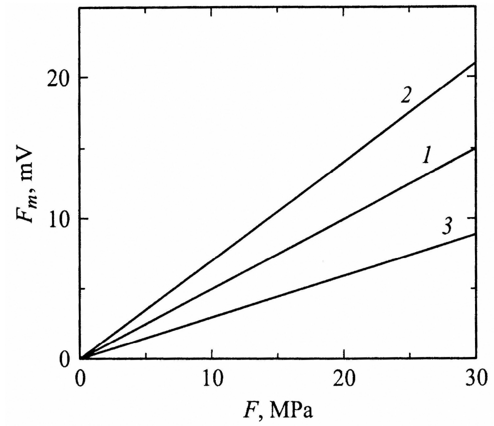

Fig. 3. *Mechanoelectric potential as a function of the compressive mechanical load F measured without electric polarization (1); in the case where the polarities of the electric potentials coincide, that is, where F_m and F_e have the same sign (2); and where the polarities of the induced electric field and the electric polarization are opposite (3) .*

Figure 3 shows the induced electric potential F_m as a function of the mechanical load. Line *1* corresponds to no electric polarization; line *2* corresponds to the case where the polarities of the induced electric field and electric polarization are the same, that is, where F_m and F_e have the same sign. Line *3* corresponds to the case where the polarities of the induced electric field and electric polarization are opposite. All the dependencies are linear in this range of loads, but they have different slopes.

Formally, one can introduce the electromechanical modulus of a material by analogy with the piezoelectric modulus:

$$E = F_m \pm \Delta F$$

In our experiment, it would make no sense to measure the absolute value for the modulus, because it depends on the probe design, its size, the gap between the probe and the sample, etc. However, the relative variation in E is characteristic for the effect of mechanical stress on an IEF at simultaneous electric polarization. It was found that the electric modulus increases (decreases) when the polarities of the electric fields induced by the electric and mechanical polarizations are of the same sign (opposite in sign).

Figure 4 shows variations in the IEF potential when the mechanical load is constant and the potential of electric polarization is varied. Three sections can be separated in the line shown in Fig. 4. The point on the vertical axis corresponds to the IEF potential without any electric polarization, i.e., to $F_e = 0$. Section *1* corresponds to the case where the electric and mechanical polarizations are of the same sign. Here, for the same load, the sample's response to the stress is stronger, so the modulus increases. Sections *2* and *3* correspond to the case when EF and IEF are opposite in sign. In this case, the electromechanical modulus decreases and, at a certain point, the sample does not react to the mechanical load *F** at all. It is interesting that a further increase (in magnitude) of the negative polarizing electric field (at the moment t_3) causes the potential to appear again when the mechanical load is applied, but in this case the potential is negative. So, a rather complex interaction occurs between the fields of electric and mechanical polarization.

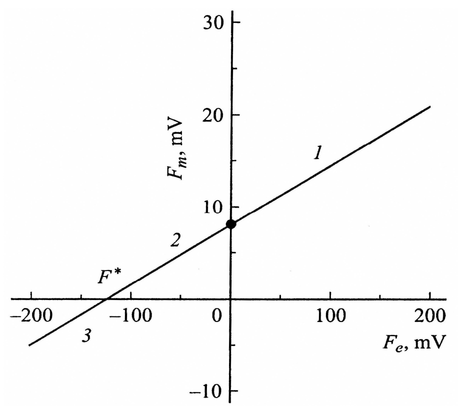

Fig. 4. *Dependence of the electric potential F_e on F_m.*

There is another parameter of great interest, especially for practical applications. Let us consider Fig. 2. When the IEF polarities induced by the electric and mechanical fields coincide, the total potential Ψ increases under load (upper part of Fig.2), and the total potential decreases under load if the polarities mentioned above are opposite (bottom part of Fig.2). Let us introduce the generalized parameter

$$\psi = (+\Psi) + (-\Psi),$$

which is the sum of two electric potentials equal in magnitude that arise on the opposite-polarity electrodes when both the load and electric field are applied simultaneously. This parameter turns out to be the sum of the potentials measured under load. This dependence is linear because it is the sum of two linear functions, *2* and *3* in Fig. 3. Moreover, it is almost independent of the electric polarizing field. As the field increases, the slope of line *2* grows but the slope of line *3* decreases. For this reason, this parameter may be used for measurements of unknown mechanical stresses, e.g. in the bulk of rocks. In practice, estimation of mechanical stresses by this method is complicated by the relaxation of the IEF [4]. Therefore, this technique is more suitable for measurements of variations in mechanical stresses, which are equally important for forecasting dynamical manifestations of macroscopic breakage, in particular, in an earthquake epicenter at the active stage.

3. Discussion

Thus, our data provide compelling evidence in favor of interaction of the electric fields induced by mechanical and electric polarizations. This interaction is not limited to simple addition of the field potentials but is more complex in nature. The phenomenological studies presented in this paper are insufficient for a complete understanding of this phenomenon. Theoretical development of a microscopic model, based on materials with a simpler structure, is necessary. However some hints as to the direction of development for such model can be obtained from an experiment by comparing the induced electric fields under compressive and tensile stress.

The simplest way to make such comparison would be to bend the sample. The corresponding experimental setup together with results obtained is presented in Fig. 5. One end of a beam-shaped quartz sample was fixed, and a bending moment was applied to the other end. The registering probe was rigidly fixed at some place, and compression or tension at this point was produced by the direction of the applied bending moment. Figure 5b shows that the induced electric fields are opposite in sign for compression and tension. Moreover, the magnitude of the electric field is strongly affected by the gradient of the mechanical stress field.

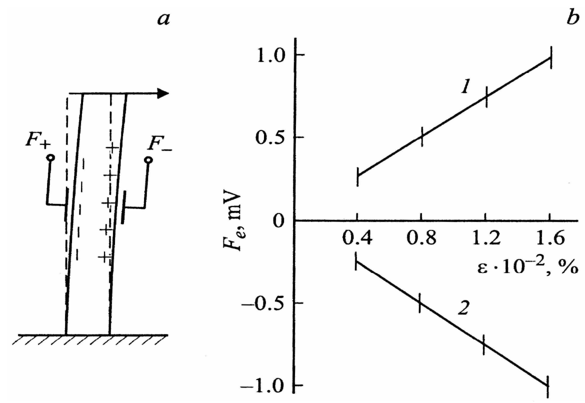

Fig. 5. *Bending experiment: (a) - the field distribution and (b) - the induced electric potential F_e as a function of deformation at the bending of the sample for the cases of compression (1) and tension (2).*

An attempt was made to relate the IEF to the orientation of dipoles by the gradient of the mechanical stress field [8]. It is noteworthy that the appearance of IEF under the action of a mechanical stress field is a rather universal phenomenon. Manifestations of this effect for quartz glass and marble are qualitatively similar despite the great difference in the physical properties of these materials. Because of this similarity electromagnetic phenomena occurring at deformation and destruction of dielectric solids (in particular, rocks) can be treated on common grounds.

In [9], the appearance of electromagnetic impulses at the formation of cracks was explained in terms of the separation of charges on the crack's walls. Without denying this mechanism of generation of electromagnetic impulses, we can suppose that all dynamic processes, including the formation of cracks, must cause drastic changes in local mechanical fields and, therefore, in the induced electric fields accompanied by emission of electromagnetic impulses. This universal mechanism can explain the electromagnetic phenomena, both static and dynamic, that occur in epicenters of rock bumps and earthquakes.

Finally, one can suggest a procedure for registering dynamic changes in a rock massif. Electrodes for the electric polarization of the massif's section are fastened at some distance from each other. The applied electric field would be about a few V. The probes for registering the induced polarization of the segment are placed near the electrodes. When drastic changes in the stress state occur, the massif's response is registered by the electrometers. The responses registered at the positive and negative electrodes are expected to be different, and thus one can determine the direction or gradient of the mechanical field involved.

4. Conclusions

Thus, the thermoelectrophysical phenomena in rocks have the main features similar to those of classi? Cal solid dielectrics, but these effects are complicated by the nonuniform structure and composition and a higher sensitivity to ambient conditions. However, some conclusions can be drawn even now. 1. Polarization in a mechanical field is proportional to the mechanical field gradient (elastic force) and is elastic in its character; i.e., it follows the load (elastic strain) without delay. 2. The relaxation under weak electric polarization and elastic deformation of the glass and marble sam? ples occurs due to weakly bound impurity ions and is a thermally activated process.

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