Failure Precursors in Rocks and Concrete

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Abstract. We monitor the damage process in different types of rocks and concrete specimens during laboratory fracture tests by low-frequency acoustic emission (elastic emission or ELE) analysis. Specimens made of dry Green Luserna Granite and concrete enriched with Iron are subjected to compressive loading at constant displacement rate and under ordinary room conditions. ELE signals are detected by applying to the specimen surface an accelerometric transducer, sensitive in the frequency range from few Hz to 10 kHz.

We find that irreversible deformations are associated with relative electrical resistance variation, which is monitored by using copper electrodes coupled to specimens by conductive silver paint and connected to a multimeter. The experimental results show that ELE activity and change in electrical resistance are strictly correlated during the entire loading process and precede the failure of all tested specimens. These two techniques are complementary for damage monitoring in rocks and concrete.

Introduction

Damage in solid materials mainly consists in the creation and growth of micro-cracks and micro-cavities, resulting in a diminished strength until failure. Damage monitoring is valuable for hazard mitigation due to the criticality of damage processes which suddenly can turn into structural and material failures. As a highly damaged volume element with inner cracks is hardly distinguishable from a undamaged one, it is crucial to define a damage variable, representing the deteriorated state of the material, which can be directly measured. Historically, a damage evaluation criterion has been introduced in the field of fatigue with the Miner's rule, $\Sigma\, n_i/N_i$, where n_i is the number of cycles accumulated at stress σ_i, N_i is the number of cycles to failure at stress σ_i and the summation extends over the different stress levels [1]. Numerous methods can be applied to measure damage defined (in the sense of continuum mechanics) as the effective surface density of micro-fractures and cavities in any plane of a representative volume element [1,2]: direct methods such as the observation of micrographic pictures and the measurement of the variation of the density cover the necessity of evaluating damage within broken components in order to find out the causes of accidents; non direct methods, such as the measurement of the variations of the elastic modulus, of the ultrasonic waves

and of the cyclic plasticity response, which are destructive as they need the manufacture of laboratory specimens for mechanical testing; non direct and non destructive methods for which no specimen is needed, such as the measurement of the variations of the micro hardness and of the electrical potential. Generally speaking, non direct methods cover the necessity of formulating the constitutive equations for the engineering materials to predict their damage evolution. In particular, non destructive methods are more flexible as they can be applied both on specific specimens and also “in situ” for control and security purposes on structures in service. Measurement of electrical resistance variations [3,4] and acoustic emission (AE) analysis [5] are two of the best non destructive methods for real time damage detection on rocks and concrete structures.
It has been demonstrated that the electrical resistivity of rock is highly dependent on the porosity [6]. In fact, for saturated rocks, Archie’s law has been established between porosity and electrical resistivity of the solid-fluid system. For dry rock, toward which the present study is oriented, it seems reasonable that the electrical resistivity should increase as microcracks open within the material. Since microcracks open as material is stressed closer and closer to its failure point, it appears that there should be a correlation between electrical resistivity and cumulative damage.
The underlying concept is that irreversible damage consisting in large cracks formation and growth causes irreversible variations of electrical resistivity and is revealed by the onset of low-frequency AEs, recently referred to as elastic emissions, or ELEs.
The objective of the present study is to investigate the possible correlation of electric resistivity with accumulating damage, measured by the accumulating number of ELE events, in dry rocks.

Damage measurements by ELE and electrical resistance variation

Damage can be defined in the sense of continuum mechanics as the effective surface density of micro-fractures and cavities in any plane of a representative volume element, taken as the smallest volume on which a density may represent a discontinuous state (micro-cracks, micro-cavities).
If **n** is the normal which identifies the area S of a section of a volume element V, and S_0 is the total area of the defect traces on this section, $D_{\mathbf{n}} = S_0/S$ measures the local damage relative to the direction. The damage variable can take all values between $D_{\mathbf{n}} = 0$ (undamaged or virgin state) and $D_{\mathbf{n}} = 1$ (rupture of V into two parts along a plane normal to **n**). From the mechanical point of view, the damage variable D quantifies the deviation from linear elasticity in the one-dimensional problem, $\sigma = E\,(1-D)\,\varepsilon$, where σ, ε and E are respectively stress, strain and Young’s modulus of the undamaged material [1,2].
The accumulating damage can be measured by the accumulating number of ELE events weighted by their magnitude [7]:

$$D \propto \sum_i 10^{m_i} , \tag{1}$$

where m_i is the magnitude of the i-th ELE event, the sum is extended over all detected events preceding material failure. The proportionality relationship, $m_i \propto \mathrm{Log}\, s_i$, where s_i is the crack area generating the ELE event, assures the consistency of Eq. (1) with the definition of damage variable as surface defect density. In fact, Eq. (1) is proportional to the total area of the ELE source cracks:

$$D \propto \sum_i s_i , \tag{2}$$

The electrical resistance R of the undamaged specimen of length l, cross-sectional area S and resistivity ρ is expressed as:

$$R = \rho \frac{l}{S}, \tag{3}$$

whereas, for the damaged specimen:

$$R' = \rho' \frac{l'}{S'} = \rho' \frac{l}{S(1-D)}, \tag{4}$$

where the effective current-conducting area S' is purely affected by damage and the plastic strain is neglected.
Assuming that the specimen volume increases with damage due to crack opening, a relation between the damage D and the relative variation of density or porosity can be derived [1]:

$$D = \left(1 - \frac{\gamma'}{\gamma}\right)^{2/3}, \tag{5}$$

where γ and γ' are the density in the undamaged and the damaged state.
The resistivity ρ is affected by the damage only by means of the density variation as expressed by Bridgman's law [1,4]:

$$\rho' = \rho\left(1 + K\frac{\gamma - \gamma'}{\gamma}\right) = \rho\left(1 + KD^{3/2}\right), \tag{6}$$

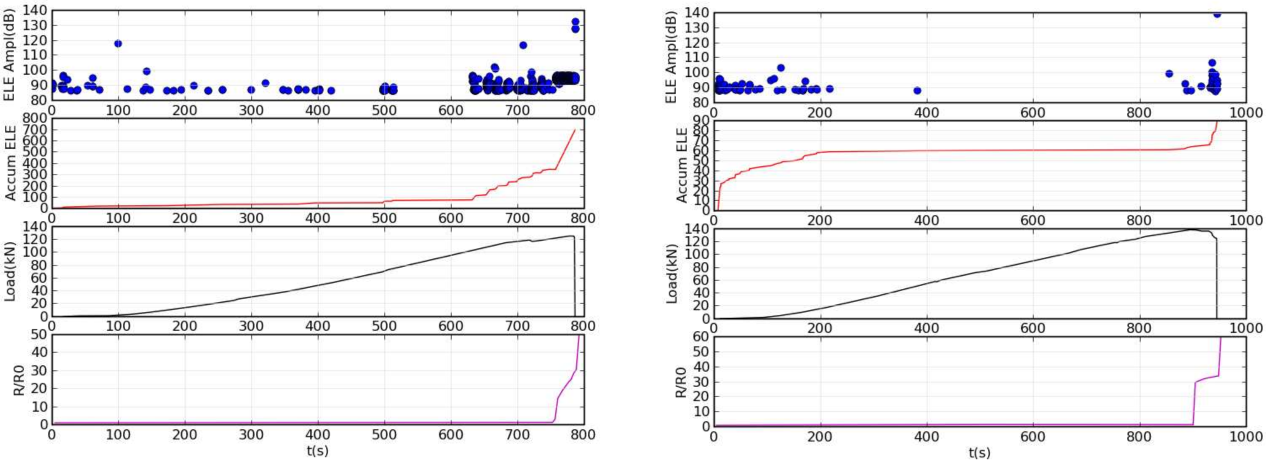
where K is a material parameter and Eq. (5) is taken into account.
The relation between electrical resistance variations and accumulating damage is obtained by Eqs. (3), (4) and (6):

$$\frac{R'}{R} = \frac{1 + KD^{3/2}}{1 - D}, \tag{7}$$

when $D = 1$, $R' \rightarrow \infty$, corresponding to the specimen rupture.

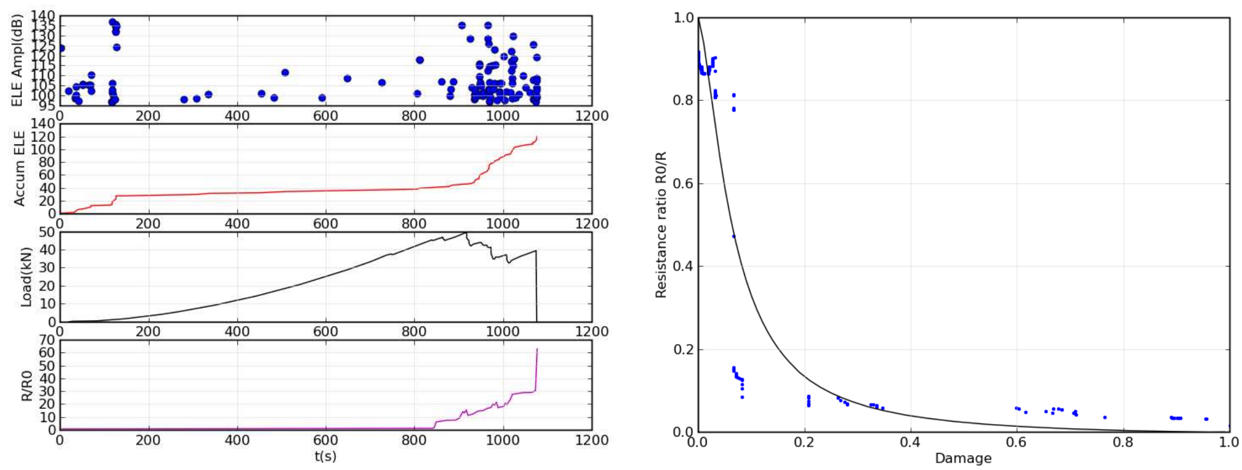
Experimental procedure and results

Here, electrical resistance measurement are carried out to detect damage in one cylindrical Green Luserna Granite specimen (diameter 52 mm, height 50 mm) and two prismatic mortar specimens (section 40×40 mm^2, height 160mm), the latter enriched with 10% of iron oxide in weight to increase the electrical conductivity. All specimens are subjected to uniaxial compression till failure at constant displacement rate of 2 μm s^{-1} for mortar and 1μm s^{-1} for granite, using a servo-hydraulic press with a maximum capacity of 500 kN.
The electrical resistance measurement are conducted using the constant voltage method, where two copper electrodes are located symmetrically with respect to each other on opposite faces, parallel to the load axis, at the half height of the specimen. The electrical conductivity of the specimen is improved with a deposition of silver paint on the two faces.



(*a*) (*b*)

Figure 1: ELE time series, accumulated ELE number, load history and relative electrical resistance variation (R'/R) as functions of time for mortar specimens.



(*a*) (*b*)

Figure 2: ELE time series, accumulated ELE number, load history and relative electrical resistance variation (R'/R) as functions of time for the granite specimen (*a*); fitting curve of Eq.(7) correlating resistance ratio (R/R') with damage (D) based on ELE measurements according to Eq. (1), where m_i = Log(a_{max}/1μmμs^{-2}) and a_{max} is the peak amplitude of the *i*-th ELE pulse (*b*).

The electrical resistance is monitored by connecting the electrodes to a multimeter (Agilent model 34411A), which was programmed to acquire resistance values every 0.1 s in real-time measurement.

For all specimens, the initial value R of the electrical resistance was measured at the beginning of each compression test. Afterwards, the variation of electrical resistance was monitored until the specimen collapse, calculating the ratio R'/R.
The reliability of resistance measurement is verified by using simultaneously the acoustic-emission (AE) monitoring technique. Here, we focus on elastic emissions (low-frequency AE), or ELE, using a piezoelectric accelerometer working in the range of 1 to 10 kHz. The ELE pulses are characterized by the output response of the calibrated accelerometer (charge sensitivity 9.20 pC/m s^{-2}), expressed in mm s^{-2}. Data is acquired at a sampling rate of 44.1 kHz for the entire duration of the tests [8].
In order to filter out environmental background noise, we set the detection threshold at 40 dB (referred to 1 μm s^{-2}). In this way, we verify that no signals are detected before the beginning of the test. Furthermore, we proceed to the identification and quantification of the mechanical noise of the press during the test, finding ELE signals purely generated by damage above 86 dB for mortar and 97 dB for granite.
The time series of the ELE amplitudes, the accumulated number of ELE events, the applied load on the specimen and the relative electrical resistance variation (expressed as R'/R) are shown as functions of time in Fig.1.
Both mortar specimens show a linear load vs. time diagram with an abrupt decrease in the load-carrying capacity after reaching the peak load (brittle behaviour). Except for the initial transient (0-200s) of ELE activity emerging when the press platen is brought into contact with the second specimen (see Fig.1(*b*)), abrupt increments of the ELE number in time are closely correlated with likewise abrupt variations of the electrical resistance in the late stages of the specimen life.
Actually, the granite specimen exhibits a quasi-brittle behaviour with intermediate load drops, signature of an ongoing damage process which is still revealed by abrupt increments of the electrical resistance and the ELE activity.
Therefore, both bursts of ELE activity and significant variations of the electrical resistance occurring in rocks and concrete seem to be valuable fracture precursors, especially when Hooke’s law is strictly followed till the specimen failure (Fig. 2(*a*)).
So as to illustrate the validity of Eq. (7), we correlate damage measurements based on ELE data, according to Eq. (1), with the electrical resistance variations in granite (Fig. 2(*b*)). The fit yields K = 55.13, confirming that the resistivity of rock is highly dependent upon the porosity.

Conclusions

Damage analysis can be performed investigating variations in the electrical properties of the material, in particular the electrical resistance. In fact, it is clear that discontinuities created during damage process increase the electrical resistance of material. Experimental studies observe that the onset of ELE, which are associated with macro-discontinuities, is in close time correlation with variations in the electrical resistance of material.
We investigate the validity of a direct relation between the damage variable, defined in continuum mechanics by the sum of all microfracture surfaces and experimentally quantified by the sum of ELEs weighted by their magnitude, and electrical resistance variations.
This study is of remarkable interest as it suggests the use of electrical resistance measurements with simple and inexpensive equipment to enhance monitoring systems based on the AE technique.

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