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THE KINETIC STUDY OF ROCK FRACTURE IN LABORATORY PRESS EXPERIMENTS

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Abstract: Methods of physical kinetics were used to describe the process of rock failure in laboratory and field experiments. The results of experiments demonstrated a good agreement with the theoretical model predicted three main stages of failure process. Transfer from 3-D to 2-D model is discussed as a possible way of predicting of the time of rock failure.

Key words: geotechnics; seismology; rockbursts; earthquakes; physical kinetic; physical model; rock failure process.

1. INTRODUCTION

Predicting of large and medium scale seismic events such as earthquakes and rockbursts presents one of the most important problems of modern geophysics. It is believed that this problem can be reduced to defining quantitative physical criteria of loosing the stability of rock massif or, in other words, to finding earthquake or rockburst predecessors which are understood as anomalities of a certain measured physical field observed during a relatively long time before the earthquake. However, the existence of a large number of such predecessors which do not often co-relate with one another and are local in space and time shows inefficiency of this approach to prediction of failure of geophysical media. We believe the main disadvantage of this approach to be the fact that the process of the preparation of strong seismic events is exluded from consideration. It is only the final stage of the event that is studied, which can develop in different ways due to its highly stochastic nature, making it practically impossible to obtain invariant predecessors. In this connection, it seems useful to consider the process of rock massif failure preparation as a whole. This can be done by the theory of physical kinetics. Primarilly the kinetic approach to the description of failure process was formulated by Zhurkov (1957) for polymeres and later was developed by Regel et al (1974), Petrov (1981) and others for rocks. This approach also made it possible to obtain new results in solid state physics and chemistry, see e.g. Mikhailov (1972), Anikolenko and Mikhailov (1976).

1.FORMULATION OF THE PROBLEM AND THE PHYSICAL MODEL

As it is known, the crucial role in the failure process is played by microstresses which exist a priori in all rocks due to the microheterogeneity and microanisotropy of the geophysical media. The presence of such powerful energy concentrators causes microcracks which grow in number and size as the deformation develops. The process of stress cracking demands overcoming of a set of potential barriers caused by interatom interactions. A kinetic equation adequately describing crack accumulation process should at least take into account the heterogenic nature of potential barriers (activation energy distribution). In this case, one should give up an attempt to describe the development of individual cracks, but try to describe the statistic ensemble as a whole based on generalized energy parametres. Taking into account the potential barriers energy distribution $f(E)$ an equation describing the kinetics of defect accumulation with time can be written as in the work of Anikolenko and Mikhailov (1976):

$$N(t)=\int f(E)\exp[-k(E)t]dE \qquad (1)$$

where $k(E)$ is the rate constant for overcoming potential barrier during the joining of two separate defects. Assuming a thermoactivating nature of the crack formation process, this rate constant may be written in the following general form:

$$k(E)=k_0\exp(-E/kT)$$

where k_0 is a constant factor independent of the energy, k - Boltzmann constant, T - temperature.

Solving an inverse problem for the equation (1) one can obtain $f(E)$ which allows to describe the geophysical media stress development process in terms of energy distribution and, finally, obtain information on the elementary act of the mechano-chemical reaction at the molecular level. The presence of various additional chemical factors in the geophysical media which affect k(E), e.g. fluids, makes this problem a very compicated one and requiring additional special investigation.

However new and useful information on the physics of the process can be obtained by analyzing the formal kinetics of rock fracture without complicated mathematical calculations. Let us assume, in the same manner as Chelidze (1987) that the rate constant of the interaction between defects i and j has the following form:

$$k(r)=k_o\exp\left(\frac{-2r_{ij}}{a}\right) \qquad (2)$$

where r is the distance between these defects and k and a are constants. Such a form of the rate constant does not contradict the assumptions about the k(E) form in equation (1), because it is clear that at the constant temperature a higher activation energy is needed to overcome a wider barrirer. So the equation (1) can be replaced with a kinetic equation which takes into account the barrier width distribution:

$$N(t)=\int f(r)\exp[-k(r)t]dr \qquad (3)$$

where the so-called distribution of free volumes (see Mikhailov and Anikolenko (1977) and Anikolenko (1992) may be used as f(r):

$$f(r)dr = \frac{4\pi r^2\, dr}{4/3\pi \cdot r_o^3} \exp(-r^3/r^3{}_o) \qquad (4)$$

where $r = (3C/4\pi)^{-\frac{1}{3}}$ is the mean distance between the defects existed at the beginning of the observations, with the defect concentration equal to C. Than substituting (2) and (4) into (3) we shall obtain:

$$\ln[N(t)/N(t_o)]=\left(\frac{a}{2r}\right)[\ln^3(k_o t) - \ln^3 (k_o t_o)] \qquad (5)$$

where t is the time of beginning the observations. The physical sense of the right side of the equation (5) consists in the decrease of free volumes at the rate proportional to ln t.

In case of uniform distribution

$$f(r)dr = \frac{dr}{r_{max} - r_{min}} \qquad (6)$$

instead of equation (5) we shall obtain the following equation:

$$\frac{N(t)}{N(t_o)} = \frac{a}{2(r_{max} - r_{min})} \ln\left(\frac{t}{t_o}\right) \qquad (t >> t_o) \qquad (7)$$

which describes defect concentration as a linear function of the logarithm of time. This situation corresponds to the case when the distance between two interacting defects is considerably shorter than the distance to another pair of interacting defects (the so-called kinetics of pair interactions).

It follows from the above that by solving the inverse problem for equations (5) and (7) we can obtain data on the parameters of the distribution f(r), as well as on the parameter a responsible for the elementary act of the mechano-chemical reaction. This problem demands a separate and more detailed study. Useful information on the rock fracture process can be obtained however by analyzing the nature of kinetic dependences without calculating any of the parameters contained in equations (5) and (7).

2. COMPARISON WITH THE EXPERIMENTAL RESULTS

With this purpose, let us consider the results of several laboratory experiments for rock failure. The forming defecrs were registered by means of the method of acoustic emission. Fig. 1a shows a typical differential spectrum of acoustic emission with loads acting for a long time till the sample was destroyed by the formation of a major crack crossing it at an angle approximately 45 . Due to the stochastic nature of the defect accumulation process in the sample, interpretation of separate stages of the process seems to be rather ambiguous.

Let us now consider an integral curve (Fig.1b) describing the total number of acoustic emission events versus time t. As shown by the experiments, such curves are very smooth and demonstrate an initial slow growth followed by a more intensive growth and, finally, a plato.

As shown in Fig.2, where the same curve is plotted in the coordinates, practically 85 per cent of its length (with the exception of a short initial and short final segments) is in good agreement with the linear dependence of the equation (7). Such a dependence permits one to assume that the linear part of the kinetic curve describes the process of interpair interaction of clusters generated in the sample under the load. So the initial nonlinear part of the kinetic curve evidently corresponds to the stage of formation of primary (noninteracting) clusters and the final part (also nonlinear) corresponds to the process of formation of the major crack which interferes with the process of interpair interactions throughout the crack's surface.

The above considerations are in good agreement with the mechanical theory of rock failure of Sadovsky (1984) which shows that with every new stage, a rock destruction process involves structures of a larger and larger scale. From the physical point of view this means that with time the system has to overcome potential barriers of larger widths, the average waiting time for elementary interactions increases and the process (Fig.1b) seems to slow down.

As follows from equations (5) and (7), the average widths of the overcome barriers increase proportionally to the logarithm of time. So the distribution f(r) as well as the parameter a can be obtained from equation (7). However to avoid the external factors affecting the sample one should carry out a series of experiments at various loading rates using the same kind of specimens.

These conclusions can be confirmed by plotting the curve from Fig.1b in the coordinates of equation (5). As seen from Fig.3 the curve shows three separate linear segments the first two of which can be defined, according to Kuksenko (1984), as a stage of accumulaion of initial defects followed by their interpair interaction. The third segment of the curve evidently corresponds to the generation of a quasiplane major crack, i.e. transition from a 3-D to a 2-D solution of the equation (3).

3.DISCUSSION

And finally, let us discuss an experiment in which a sample was loaded into a press-machine together with iron parts or cylindric form which increased the stifness of the machine. This allows one to smooth out the dynamics of the sample failure during the final stage and obtain more detailed data. Fig.4 shows a typical kinetic dependence for experiments of this kind. As one can see, the curve consists of two segments, each of them similar to the curve in Fig.1b. The beginning is characterized by an active growth of the number of acoustic emission pulses, then a "quiet" period follows, then the sequence repeats. The data of the experiments show that every new rise of the kinetic curve is preceded by the formation of a major crack splitting the sample into separate parts. So every next step of the kinetic curve corresponds to the process of the failure of its separate fragments, i.e. to the transition to a lower level of volume hierarchy.

Fig.5 presents a longterm kinetic dependence for an experiment of this type plotted in the coordinates of equation (7) . In addition, in the course of this experiment the sample was completely unloaded and then fully loaded again. As seen from Fig.5, the kinetic curve falls into five linear segments and this dependence is also observed after the unload/load cycle. This proves that the principle of self-reproduction is maintained with the transition to a new level of volume hierarchy. If we treat each of the linear segments as an independent curve, i.e. as a separate experiment similar to Fig.2, and redefine t in equation (7) accordingly by associating it with the beginning of each of the linear segments, we shall see that these curve segments will have very close values of the slope tangents. This fact is another evidence of the self-reproductive nature of the failure process.

One more interesting conclusion which we believe follows from these experiments is the fact that analysis of their physical meaning enables one to interpret such well-known seismic phenomena as seismic gaps preceding intensive shocks and explain the earthquakes recurrence curve. Taking into account the self-reproductive nature of the destruction process one can suppose that seismic gap corresponds to the moment when the kinetic dependence of an integral number of registered earthquakes comes to the plato, as e.g. in Fig.1b. At the same time it is clear that seismic gap does not present a real decrease in seismic activity as it seems, because it is not observed in the N(t) vs Log t graph. Moreover, seismic gap increases the probability of high-energy events (rupture) as most of the low-energy events have already happened. From the point of view of earthquake prediction this means that a seismic gap is really an efficient predecessor of a strong rock burst or earthquake wherever it is caused by the formation of a rupture crack. This is accompanied by a full or partial discharge and reproduction of the kinetic dependence similar to Fig.5. However in case the discharge as a result of a powerful earthquake is caused by faulting due to techtonic processes, seismic gap may not be observed at all, because such events may correspond to the rising segments of the kinetic curve (Fig.1b), i.e. before it has reached the plato.

Thus the analysis of integral kinetic curves obtained as a result of laboratory and field experiments provides new data on the mechanism, structure and kinetics of the process of the failure of geophysical media and makes it possible to give a physical interpretation to the phenomenon of seismic gap as well as to explain the earthquake frequency graph.

4.CONCLUSION

The results of model and field experiments are in a good agreement with theoretical equations based on kinetic approach. The proposed kinetic model can be used for long-term forecasting of strong seismic events and rockbursts in mines as well as for explanation of the nature of well-known seismic phenomena such as seismic gap.

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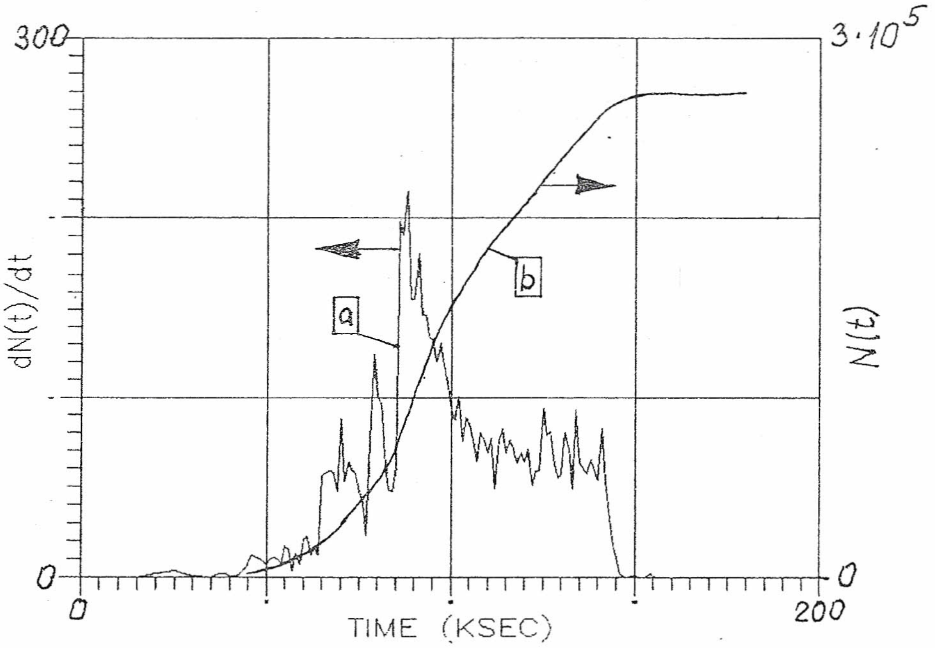
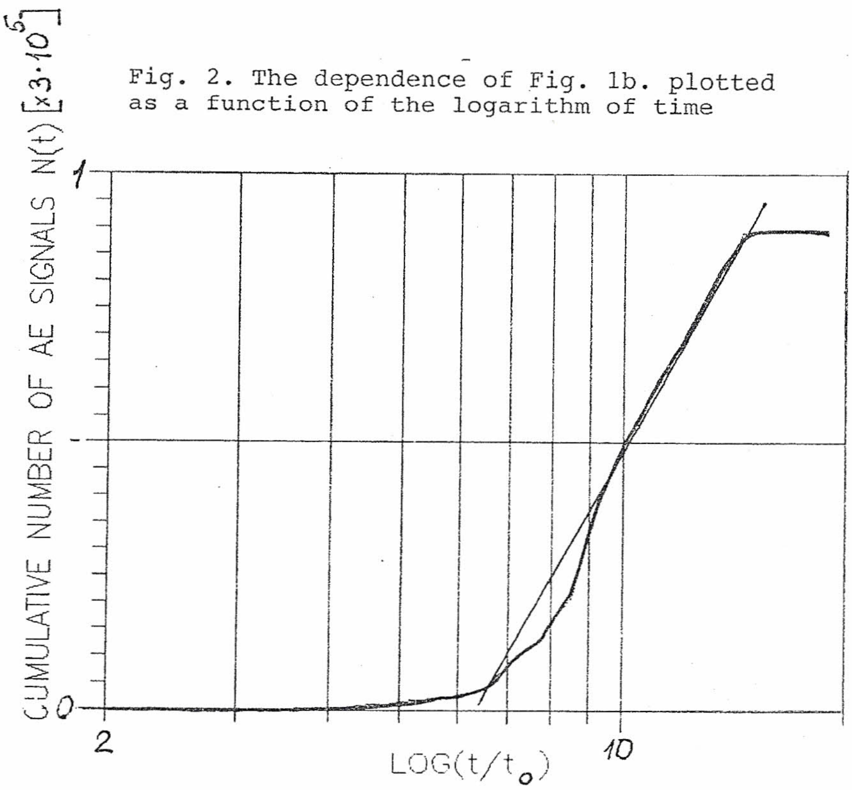


Fig. 1. The failure of a sandstone sample by the test mashine: a differential spectrum (a), and an integral spectrum (b)

Fig. 2. The dependence of Fig. 1b. plotted as a function of the logarithm of time



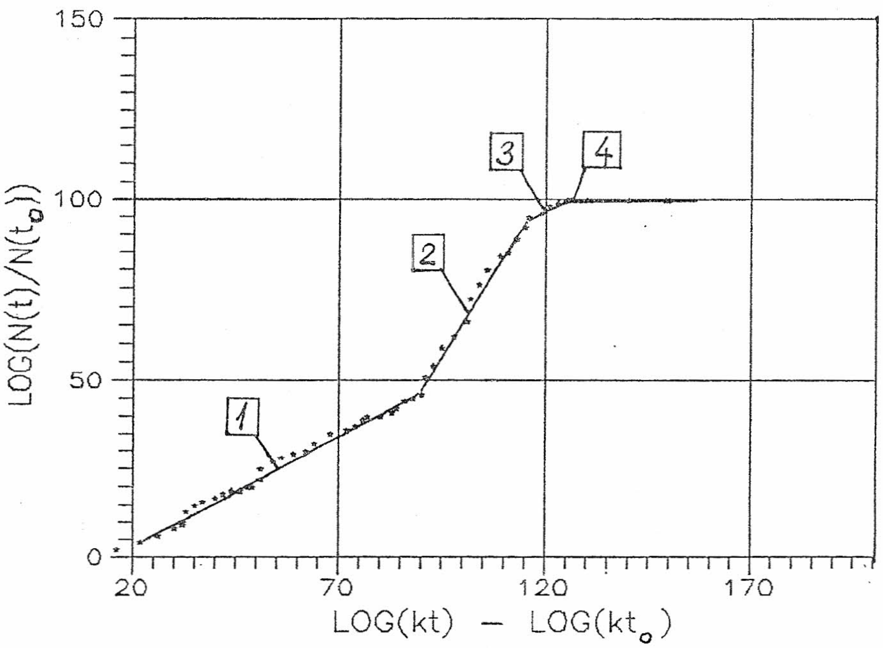
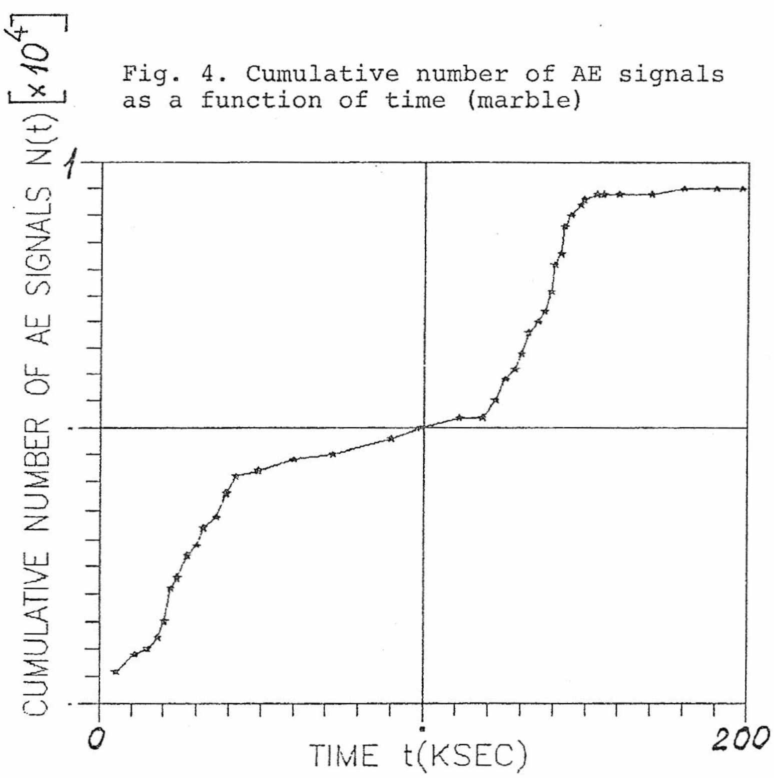


Fig. 3. The kinetic dependence for granite failure in laboratory experiments plotted in the coordinates of the equation (1):
1 - generation of initial defects; 2 - generation of cracks due to the joining of the lower rank defects; 3 - growth of the major crack; 4 - failure of the sample

Fig. 4. Cumulative number of AE signals as a function of time (marble)



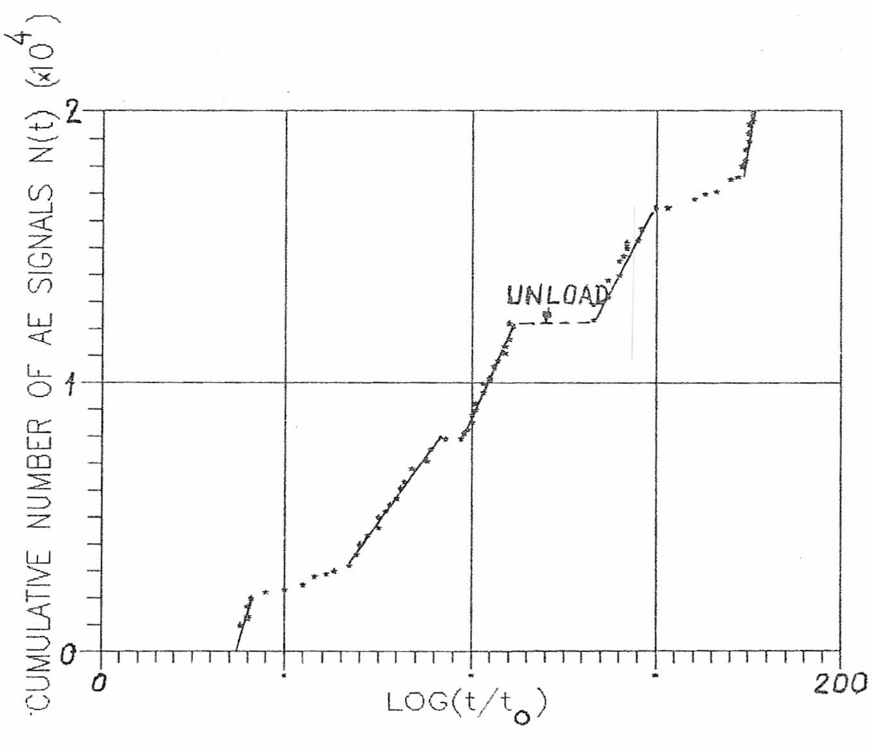


Fig. 5. Cumulative number of AE signals as a function of logarithm of time (marble)