The acoustic measurements for assessment of dynamic processes in rock-mass

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RESUMEN

La existencia de tensiones en macizos rocosos puede llevar al desarrollo de sistemas de microfisuras. La formación de fisuras genera emisión acústica que puede ser registrada con una instrumentación especial.

La emisión acústica, procedente de zonas fisuradas, puede ser analizada utilizando los intervalos de tiempo entre las emisiones consecutivas. Otros modelos conceptuales pueden ser también empleados en el análisis de datos.

Los procesos de absorción y flujo de gas a través de estratos de carbón originan la emisión acústica.

Los sistemas de medidas basados en los registros de emisión acústica pueden ser empleados en la protección contra hundimientos de techos, deslizamientos y explosiones de bolsas subterráneas de gases.

Palabras clave: Emisión acústica, modelos físicos, seguridad en minas.

ABSTRACT

Stress in rock-masses can develop cracks. Crack formation generates acoustic emission which can be recorded using special equipment.

The acoustic emission from cracked zones can be analyzed using gaps between acoustic energy emissions. Other models of the acoustic emission can be used.

The special attention is paid to processes of the acoustic emission originated during gas sorption and gas flow through coal medium.

The acoustic emission method can be used in assessment of rock bursts, slope slides and gas outbursts.

Key words: Acoustic emission, physical models, mining safety.

INTRODUCTION

Under the influence of stresses in rock-masses the medium is deformed. Deformation $d\varepsilon$ consists of the elastic, $d\varepsilon_{el}$, and unelastic, $d\varepsilon_{un}$, parts:

$$d\varepsilon = d\varepsilon_{el} + d\varepsilon_{un}$$

The second component in the formula depends on the king of rock and physical conditions in which the deformation takes place. Three kinds of deformation are recognized: plastic, ducle and britlle ones. Two last kinds produce cracks or sliding along the crack surface. This kind of deformation gives acoustic emission. The acoustic signals may be recorded with special equipment. The energy of signals may be estimated. They are related to the area of crack surface or its length. There are possibilities of identification of the acoustic signals and its energy. That gives methods for the assessment of the dynamic processes in the rock-medium. The acoustic methods are useful in the recognizing dynamic changes in the rock-mass, such as:

– assessment of the properties of a cracked zone which appears in the vicinity of the cavern;
– estimation of liquid and gas flow through porous media;
– prediction of soil movements;

These three aims are especially important in the assessment of rock stability during underground rock excavation and mining activity. The examples which are considered in the paper are taken from geophysical survey in Polish coal mines.

I. PROPERTIES OF A CRACKED ZONE

Each volume extracted from rock-mass produces a stress distribution around it (Fig. 1).

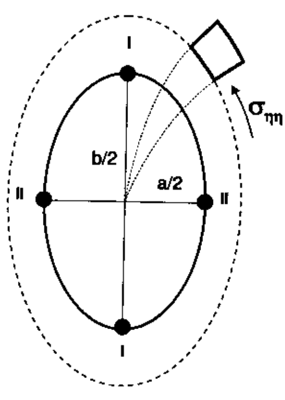

Fig. 1. Cross-section of a cylindrical roadway and formation of a cracked zone.

The distribution depends on the geometric shape of the cavity border. In particular, in a homogeneous isotropic rock-mass, the stresses which build up around roadways with eliptical cross-sections are described by the formulae:

$$\sigma^{(I)}_{nn} = \sigma^{(in)}_{x}(1 + 2\ b/a) - \sigma^{(in)}_{z}$$
$$\sigma^{(II)}_{nn} = \sigma^{(in)}_{z}(1 + 2a/b) - \sigma^{(in)}_{x} \qquad (1)$$

$$\frac{\sigma^{(in)}_{x}}{\sigma^{(in)}_{z}} = \frac{\nu}{1 - \nu} \qquad (2)$$

where $\sigma^{(in)}_{x} = \sigma^{(in)}_{z}$ –initial stresses in homogeneous undisturbed rock-mass; ν - Poisson ratio; a, b– lengths of half-axes of elipse in cross-section.

It has been proved empirically that a micro-crack zone is formed around an underground roadway. It may be assumed that the boundaries of the micro-crack zone can be characterized by the condition $\sigma_{max} = \sigma^*$, where σ_{max} is the maximal tensile stress induced by the main crack and σ^* is a constant.

The width of the zone and its mechanical parameters depend on a number of parameters, such as:

1. Initial stresses according to formula (1).
2. Variations in the distribution of mechanical properties in the rock-mass -according to formulae which show the influence os the anisotropy effect on the elastic properties.

There is also similar stress distribution in the vicinity of the lithological or physical disturbances in the rock masses. It has been proved empirically, that a micro-crack zone is formed in the vicinity of such volume. It may be assumed that the bounderies of the micro-crack zone can be characterized by the condition σ_{max} - σ^* where σ_{max} is the maximal tensile stress induced by the main crack and σ^* is a constant. The width of the zone and its mechanical parameters depend on a number of parameters, such as:

– initial stresses;
– variation in the distribution of mechanical properties in rock-mass;
– occurrence of a fracture in the vicinity of stress disturbance.

II. THE MEASUREMENT SYSTEM

The acoustic sensors change mechanical vibration into an electrical signals. There are three mechanical vibrations which may be transformed: displacement, velocity and acceleration.

Transformation is based on the inertion rules. The mass inside the sensor corpus is suspended on a very sensitive system of springs. The mechanical movement of two masses, one against another, causes induction of electrical current induced in the coil in the stable magnetic field, fixed to the sensor corpus.

Two parameters denote the acoustic sensors, sensitivity and frequency range with a constant sensitivity. The sensitivity, in general way, expresses the ratio of the amplitudes of acoustic signals picked up by the sensor and amplitudes of the recorded acoustic signals. The highest sensivities in the displacement sensors are connected with very low frequency (a few Hertzes).

Very often they are used for recording signals coming from large distances. They are used also for a special purposes (the capacity sensors, laser sensors; Ono 1979).

For the middle range of frequency the velocity sensors are used (up to 500 Hz) and for high frequency the accelerometers are the best sensors.

The sensors have a directional characteristics (the highest sensitivity in the direction of the coil movement, no possibility of picking up signals coming in the perpendicular direction).

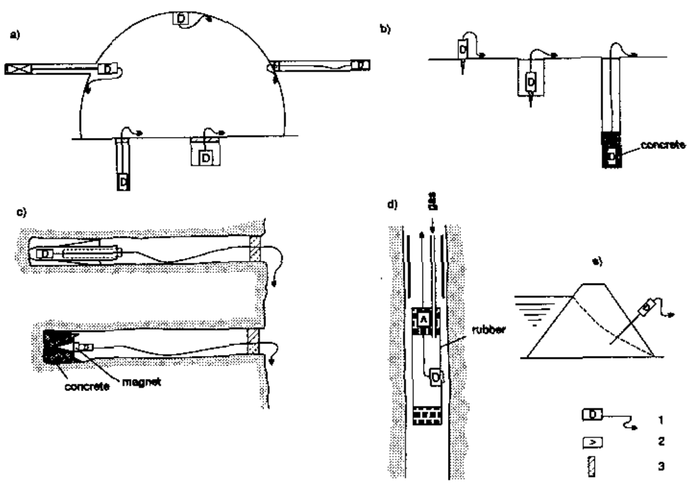

Fig. 2. Sketches of installation of seismoacoustic detectors:
a) in a mining opening (Hardy, 1982), b) at the earth's surface (or a shallow depths) (Hardy, 1982), c) in a horizontal borehole, d) a pneumatically expanding detector, e) with the use of wave-guide in a water reservoir embankment.
(1 – detector from which the signal is led by a cable, 2 – preamplifier, 3 – acoustic seal of the hole).

A way of interaction of acoustic sensors has the essential influence on the obtained results. They may be divided in the following groups (Hardy 1982, Blake 1984) (Fig. 2):

– the surface on near-surface installation in which a sensor is glued up to

the rock-surface; very often this kind of installation produces a large level of disturbances and noises;
- the installation of sensors in a shalow borehole (up to a few meters) which needs cementation or the use of special anchors. This method may help in obtaining better quality of recorded signals due to avoiding the transmition of acoustic waves trough the cracked zone in the vincinity of mining opening;
- the installation of sensors in deep boreholes (up to a few hundered meters) for recording acoustic signals which appear in underground gas deposits, e.g. during hydro-cracking; it needs a special pneumaticaly expanding anchor;
- the installation of sensors with wave-guided rod.

The registration system

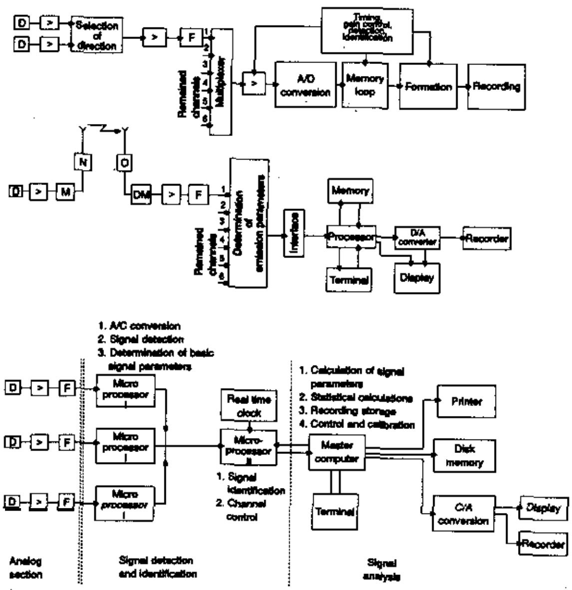

Fig. 3. Schematic diagrams of seismoacoustic equipment: a) with the basic system of signal processing (the system of spatial filtration of signals on channel 1 is indicated);
b) with the parametric system of signal processing (the system of analog radio transmission on channel 1 is indicated);
c) multiprocessor for recording and analysing of seismoacoustic signals, operating in real time (the performance of basic functions by hierarchically cooperating system of processor is outlined).
(D – detector, > – amplifier, F – set of frequency filters, M – modulator, DM – demodulator, N – UHF transmitter, O – UHF receiver).

In many professional recording systems, the pre-processing of registred data is included. The recorded information is automatically transformed into parameters such as (Fig. 3):

- acoustic activity (the number of events in a unit of time);
- intensity of released energy (total energy of acoustic signals in a unit of time);
- the statistical parameters of the signal parameters distribution;
- the localization of the signal sources.

The data pre-processing is now realized with the digital system which alow also:

- to increase dynamical range of recorded data;
- to use of the existing software system for extraction of the useful information which is contained in the measurement data.

Sometimes, the acoustic system is installed on a car making it handy in different field conditions.

III. THE ACOUSTIC EMISSION FROM CRACKED ZONE

Analysis of the empirical distribution function of the acoustic signals energy measured during underground copper exploitation and gaps between them leads to the following models (Cianciara, Marcak, 1991):

$$F_{\varepsilon}(E, D, C) = \begin{cases} 1-10^{-(D+CV^{\frac{1}{2}})V} & \text{for } V>0 \\ 0 & \text{for } V<0 \end{cases} \qquad (3)$$

where $V = \lg E/E_0$ and E_0 is the smallest recorded energy.

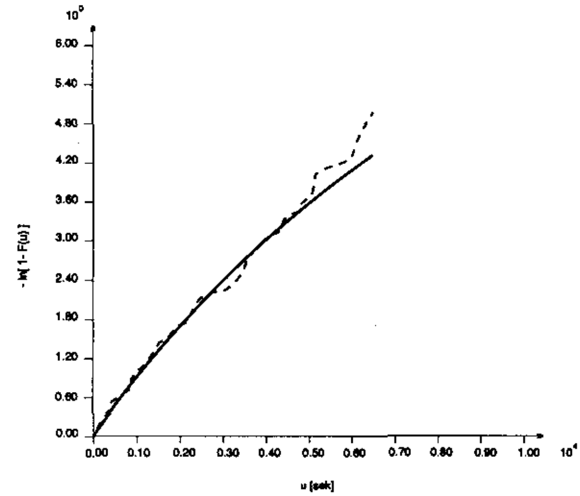

Fig. 4. The approximation of energetic distribution of acoustic signals registred in copper mine «Rudna» (Cianciara, Marcak, 1991).

The fitting of the values obtained from the model of Eq. (3) to the randomly chosen empirical distribution of acoustic signals measured in the copper mine in Poland is shown in Fig. 4.

The assumption that Poisson's distribution gives the probability of acoustic signal emision for a fixed energy E_0 leads to the formula:

$$P\,(n = k, E = E_0) = e^{[\lambda(E)\,T]}\;\frac{[\lambda(E)\;T]^k}{k!} \qquad (4)$$

where λ(E) is the expected value of the acoustic activity.

For the energy $E = E_0$ the distribution function of the gaps u (Fig. 5) between acoustic signals may be written as:

$$F_u = \begin{cases} 1 + \dfrac{1}{1\text{-}A}\,(e^{-\lambda u} - e^{-a\lambda u}) & \text{for } u>0 \\ 0 & \text{for } u<0 \end{cases} \qquad (5)$$

where $A = E_0/E_{max}$

The expected value of the gap M(u) is:

$$M(u) = -\frac{\ln A}{(1-A)\,\lambda} \qquad (6)$$

In this distribution, parameter λ expresses the number of signals in time

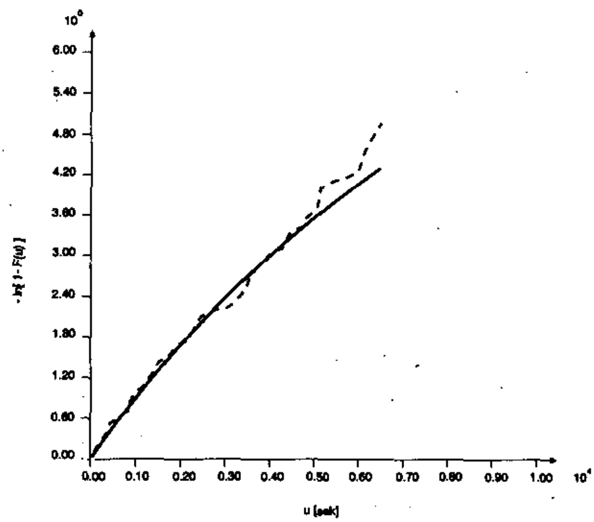

Fig 5. The approximation of the acoustic signals gaps distribution from data registred in copper mine «Rudna» (Cianciara, Marcak, 1991).

unit (the acoustic activity) and A is the measure of the energy range in which the acoustic signals may be recorded. The fitting of the signals gaps distribution to real data collected from a copper mine in Poland. The approximation of distribution of the gaps between the acoustic signals in the underground conditions acording to formula (5) is shown in Fig. 5. The parameters D, C, A, and λ_0 may be used for estimation of the acoustic emission which is treated in this model as a stationary and homogeneous process.

IV. MODELS OF EMISSION FROM THE CRACKED ZONE

An underground rock body is subjected to a continuous loading due to gravitational pressure of the overlying rock-mass. Similarly, the development of caverns in the rock gives rise to the disturbed spatial distribution of stresses that decay fast with increasing distance from the source of the distribution. Also, the anomalous spatial distribution of elastic properties in the rock-mass is the source of local disturbances in stress distribution.

The stress distribution in the tip of crack is shown in Fig. 1.

The anomalous field of stresses very often gives rise to cracks in a rock mass. However, the rock-mass is very rarely fully destroyed. The eliptical crack ocurrence with semilength C and width W introduced in an infinite medium with constant effective elastic parameters and with uniform stress σ at the boundary, neglecting elastic energy associated with crack-crack interaction, gives, according to Griffith's theory (Griffith, 1924), the total free energy change ΔF:

$$\Delta F = W\,(-B^2\sigma^2C^2 + 4\gamma C) \tag{7}$$

where:

$B^2 = 2\gamma/E$ (E is Young's modulus, γ is the unit area of the crack) and 2γ is the energy needed to separate the unit area of the crack.

The critical condition for dynamic failure of rock has the form:

$$\sigma_k = 2\gamma \tag{8}$$

where:

$$\sigma_k = B^2\sigma^2C \tag{9}$$

The following conditions should be distinguished:

(1) for $\sigma>\sigma_k$, crack growth occurs:

(2) for $\sigma<\sigma_k$, the equilibrium state may be approached where the solid un-

cracked rock, far from the sources of stress distribution, turns into a cracked but stable rock-mass near the cavern surface.

Rundle and Klein (1989) have numerically simulated the second case for an ensemble of weakly interacting elliptical cracks of varying semi-lenght C and found that a diffuse halo surrounding the cavern appears. This halo is called the fracture zone.

It has been shown (Main, 1991) that by analogy with Griffith's (1924) definition a potential energy release rate for the cracks may be defined as

$$G(P) = -\left(\frac{\partial U}{\partial A}\right)_{N_T} = \frac{B^2\sigma^2}{2}\left(\frac{\partial <C^2>}{\partial <C>}\right) \tag{10}$$

where $<C>$ and $<C^2>$ are the expected values of the crack length and square of the crack length, respectively; U is the potential energy of the systems proportional to the volume of damage, A is the total surface area of the cracks, and N_i is the number of interacting elliptical cracks of varying semi-length C.

The criterion for dynamic failure is then:

$$\sigma > \sigma_k$$

where:

$$\sigma_k = 2\gamma \tag{11}$$

The time-dependent fracturing is controlled by the plasticity of the rock material. Significant general plasticity of the rock causes the pre-existing crack tip to grow in a stable manner until its length changes the equilibrium state and the condition to propagate unstably as mean crack. The nature of a «fracture zone», its width and the density of cracks depend on environmental effects, including the porosity of the rock, the chemical composition of the fluid which saturates the rock-mass, and the temperature of the rock. There are a number of different ways in which the action of the chemical composition and temperature of the interstitial can lower the barriers to crack propagation. The presence of chemical agents in the crack tip can promote weakening reactions, known as stress corrosion (Atkinson and Meredith, 1987).

Bauer and Johnson (1979) have shown the linear increase in the crack density with increasing temperature for a quartz sample. Similar behaviour may be expected for rocks. The changes of the local structure of non-elastic deformation have the form of clusters (appearing of long cracks which are the sources of more energetic acoustic signals). It may be shown that the statistical distribution of the size of the clusters (the length of the cracks or seismoacoustic signals energy) is fractal. It means that if N_n is the number of elements and r_n the size of the elements, then:

$$N_n = \frac{B}{r_n^D} \tag{12}$$

were D is the fractal parameter and B is a constant of proportionality.

It may be shown (Gutemberg et al., 1954) that the number of acoustic events N_n with energy E_n may be related to the energy E_n by the formula:

$$\log[N_n(E_n)] = a - b \cdot \ln E_n \tag{13}$$

Parameter b is related to parameter D and may be expressed as (Turcotte, 1980):

$$D = 3/2\ b \tag{14}$$

Parameter D also shows the pattern of distribution of the source of seismoacoustic signals and one-dimensional development of crack structure is only possible if D = 1.

The distribution of microcracks length in the aureole of damage was analysed in many papers (e.g. Hireta et al., 1987; Smalley et al., 1987), showing that the fractal geometry of the crack length distribution results from the configuration entropy in the spatial distribution.

The changes in this fractal geometry or fractal parameter D are the consequence of interaction between the crack elements in the «fracture zone» and cause a time-dependent decrease of parameter b prior to dynamic failure. This means an increase of the ratio of very energetic events to all events which appear in unit time. On the other side, the increase of crack density causes the increase of G until G_c and main crack growth is a result of an ensemble of minicracks due to crack coalescence.

In empirical distribution, the first factor corresponds to the assumption of the fractal structure of the data, and the other one is the measure of limited thickness of the cracked zone.

It is obvious that the size of the aureole of damage must affect the crack length that may develop around the stress anomaly due to the waste deposits. Hence, from a practical point of view, the assumption of fractal character of the crack length distribution in this zone should be supplemented by a condition limiting the crack length and, therefore, the energy of signals emitted during fracturing. In an empirical distribution, the first factor corresponds to the assumption of a fractal structure of the data, and the other one is the measure of limited thickness of the cracked zone. The first factor in Eq. (3) is therefore the measure of changes of interactions between cracks, and the second factor is the measure of the crack-length changes. The parameter b in Eq. (13) expresses the intensity of coalescence of cracks in the investigated area.

Figures (6), (7) shows the changes of parameters in formula (3) and λ from formula (5) during exploration in copper mine. The markedly intensive changes of this parameters (decrease of B parameter increase of D parameter and activity) precede the strong mining shocks.

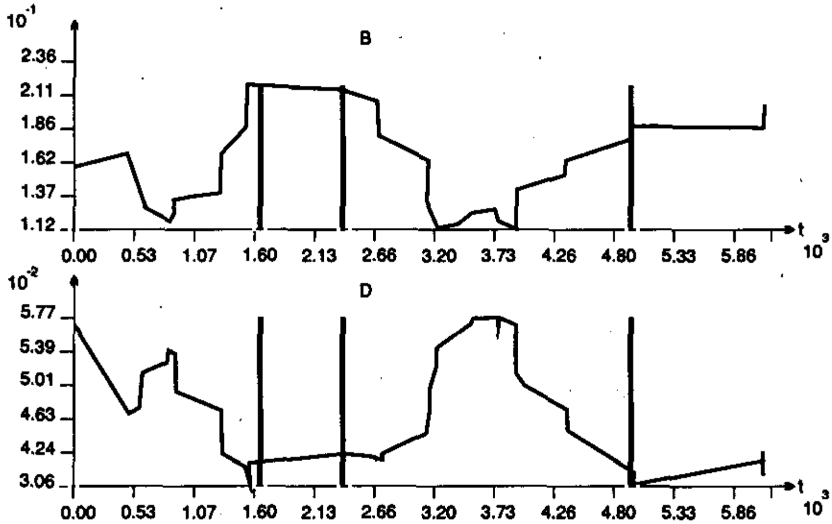

Fig. 6. Changes of parameters in formula 3 during the exploration in a copper mine «Rudna», the bold vertical lines present the moments of appear the strong mining shocks with energy greater than 5.5E + 5J (Time in seconds).

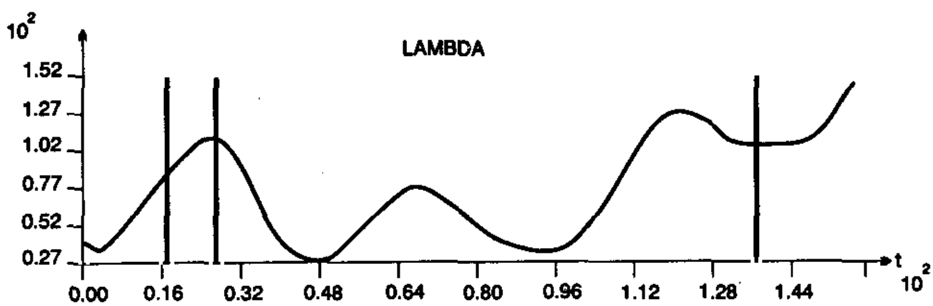

Fig. 7. Changes of parameter λ in formula 5 during the exploration in copper mine «Rudna», the bold vertical lines present the moments of appear the strong mining shocks with energy greater than 5.5E + 5J. (Time in minutes).

V. ACOUSTIC MEASUREMENTS CARRIED OUT DURING GAS SORPTION AND ITS FLOW THROUGH CARBON MEDIUM

Information on drastic desorption of gas stored in coal has significant importance in evaluation of the effectiveness of draining, or, in case of uncontrollable processes, determining the risk of gas and rock outburst. Both laboratory research and *in situ* studies have shown that dynamic changes occurring in the rock-mass due to gas flow through its pores and cracks, and the changes resulting from sorption and desorption of gas, can be recorded with acoustic methods.

The results of acoustic measurements (Z. Majewska and H. Marcak, 1987, 1989; Z. Majewska, 1990, 1991) have shown that the flow of gas through carbon medium is accompanied by the effect that can be recorded acoustically. Particularly, laboratory research has demonstrated a correlation between acoustic activity (the number of acoustic events recorded in a period of time) and flow of gas through rock to which triaxial stress is applied (Fig. 8).

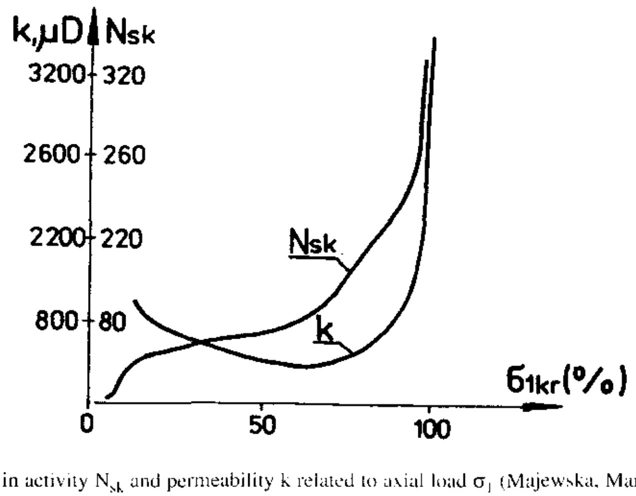

Fig. 8. Changes in activity N_{sk} and permeability k related to axial load σ_1 (Majewska, Marcak, 1989).

This correlation points to the possibility of measuring changes in permeability of a medium with acoustic methods.

Figure 9 shows the results of studies of changes in acoustic activity during exploitation of coal with long-wall rock in the «Thorez» mine in Poland, where the risk of gas outbursts was recognized.

It shows also that flow of the gas released by the coal seam during mining exploitation generates seismoacoustic signals, and seismoacoustic activity depends on the size of this flow.

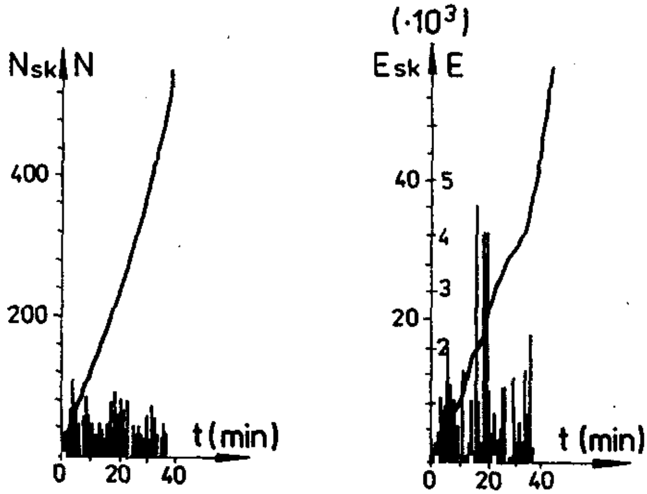

Fig 9. Example of acoustic observations carried out in the «Thorez» coal mine in Walbrzych during exploitation of a longwall threatened by outbursts (Majewska, Marcak, 1987).

Figures 10 and 11 show the results of studies of seismoacoustic activity during sorption and desorption of carbon dioxide in coal samples under laboratory conditions.

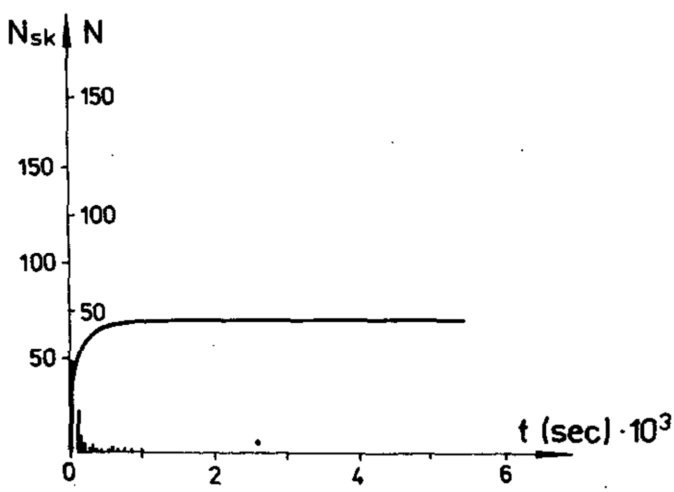

Fig. 10. Changes of the acoustic cumulated activity in a function of time during CO_2 desorption from coal samples (Majewska, 1990).

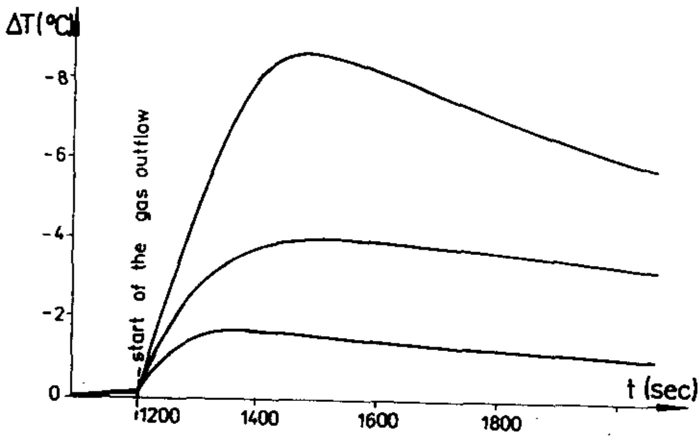

Fig. 11. Changes of the acoustic cumulated activity in a function of time during CO_2 sorption in a coal samples (Majewska 1990).

Gas entering a container with the coal sample at the time t_0 is sorbed by rock over a period of time, during which the seismoacoustic activity is measured. Similarly, after release of gas from the container at the time t_0, its desorption is followed by measuring the seismoacoustic activity. The analysis of those results shows:

- the difference in characteristics of seismoacoustic activity during sorption and desorption of gas in coal samples, both in duration of the emission and its activity;
- a rapid increase of activity inmediately after time t_0 and its relatively slow decline over time.

VI. PHYSICAL MODELS OF ACOUSTIC EMISSION SOURCES DURING SORPTION AND DESORPTION OF GAS IN COAL

It seems quite obvious that the release of gas from coal is accompanied by two processes, namely the thermodynamic change due to desorption of gas and its flow.

Acoustic experiments imply that both processes are connected with emission of acoustic signals. From the thermodynamic point of view it should be assumed that they influence each other and it would be difficult to separate them when considering physical models that describe those phenomena. An important additional effect accompanying the process of gas desorption in coal is contraction. Figure 12 shows the kinetics of carbon dioxide sorption and desorption in coal samples and the kinetics of coal expansion and contraction over time.

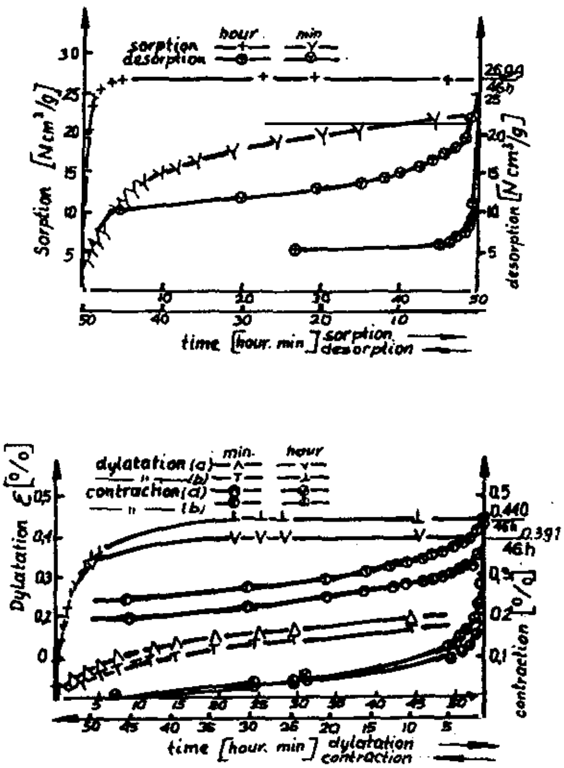

Fig. 12. The course of kinetics of sorption and desorption of CO_2 in coal and the course of kinetics of expansion and contraction % (Cegielska-Stefanska, 1990).

Measurement results shown in figures 9, 10, 11 and 12 indicate that acoustic measurements do not accompany the whole period of desorption and it may be supposed that they are connected with phenomena that accompany thermodynamic changes in coal. During identification of these phenomena attention should be paid to be the bidispersive character of the coal seam (D. J. Remner et al., 1984; S. Horpalani et al., 1986). This character makes it possible to discriminate two structural systems, of micro- and macro-pores. The macro-pore system, i.e. a network of cracks of 10^{-10}-10^{-6} m. width, is the basic drainage network. This network forms microblocks of proper coal matrix that contains micropores of 5-10 Å width in which the gas is stored. Seismoacoustic signals are the result of non-elastic deformation in the rock mass, and –in particular– of formation and deformation of discontinuity surfaces in the petrographic structure of rock. A model consisting of an aggregate of ideal spheres with a radius R may be employed to describe the mechanisms of acoustic signal formation (R. J. Whiteman et al., 1964).

If the aggregates of spheres are subjected to stresses σ_z, σ_x in two main directions, the stresses cause deformation of the spheres and in the points of contact there appear circular contact plaques with a radius r:

$$r = [3(1-\nu)(8G) - 1RTN] \qquad (15)$$

where ν is the Poisson coefficient, G –elastic module, N– load force. The contact plaque has a complex mechanical structure. It is divided into the central zone in which tangential tension is lower than friction, and the external ring in which sliding occurs. Which increasing load the central zone disappears and the contact plaques are shifted. Due to this displacement energy is released:

$$E = D \text{ x } 2r^2 (\sigma_1 + \sigma_3)(\mu_s - 2\mu_D) \qquad (16)$$

where:

x – linear magnitude of displacement
μ_s, μ_D – static and dynamic friction coefficients
D – area of the plaque

The energy of seismoacoustic signals is proportional to the energy of skid described by equation (16).

The surfaces separating structural microblocks of coal are more complex than described with model showed above and released energy depends not only on elastic properties of rock but also on the kind of gas filling the cracks and its pressure. Nevertheless, general conclusions that also apply to displacements between coal microblocks can be drawn from the model of agglomerates of spheres. They include:

- there exists a minimal limiting value of elastic energy generated by a shift along the surface of the microblock; its excess is the condition of acoustic signal recording;
- the energy of acoustic signals emitted from coal depends on the size of surface along which a shift occurs;
- the energy of seismoacoustic signals depends on the length of the displacement of the surfaces which are the source of acousting signals.

VII. SOURCE ENERGY OF SEISMOACOUSTIC ENERGY DURING THE GAS FLOW POROUS ROCK-MASSES

Considering the source of energy seismoacoustic emission it is usually assumed that the stresses causing a non-elactic strain, which is the source of seismoacoustic impulses, are the result of an external load.

It is also assumed that this load is a part of the external condition of the measuring setup. If the seismoacoustic impulses appear due to the flow of gas through the fissures in coal matrix, a different source of energy for generation of non-elastic strain that causes acoustic emission should be looked for. It could be found in the changes of thermodynamic energy proceeding in coal. Due to physico-chemical changes connected with gas release the change in the internal energy dE of a coal block should be generally regarded as the sum of changes in energy resulting from stresses generated by mass forces dE_{str}, by surface stresses on the six surfaces of the hexagon, which may approximate the shape of the block dE_{sur}, from gas pressure in pores dE_{gas}, thermodinamyc changes dE_{the}, and energy changes due to chemical processes dE_{che}.

$$dE = dE_{sur} + dE_{str} + dE_{the} + dE_{gas} + dE_{che} \qquad (17)$$

The individual elements of formula (17) may be described as:

$$dE_{the} = T\,dS,\ dE_{str} = \sigma_{str}\,dV,\ dE_{gas} = p\,dV$$
$$dE_{sur} = \sigma_{sur}\,\frac{2}{3\,(V)^{1/3}}\,dV,\ \ dE_{che} = \sum_{0}^{j} \mu_j\,dn_j \qquad (18)$$

where:

S – *entropy*, σ_{str} – *stress at the surface of the cube*, V – volume,
μ_j – chemical potential, and n_j – number of moles of the j-th component participating in the chemical process.

Equation (17) shows that the changes in internal energy in the micro-block have heterogenous origin. The two first elements of the sum (17) result from mechanical forces, the next two are the result of thermodynamic changes, and the last is an effect of chemical transformations. The equation implies that there is a possibility of transforming one kind of energy into another, particulary the transformation of thermodynamic energy into mechanical energy.

The last element of sum (17) is important in the case of gas desorption. The changes in internal energy of coal may be evaluated with the so-called vacancy adsorption theory (Krasilnikowa et al., 1977). According to this theory the adsorbing systems may be regarded as a solution consisting of adsorbed gas particles and adsorbance space W, which consists of the space elements unoccupied by the adsorbent and of volumes equivalent to the volume of molecules. The increase in chemical potential $\Delta\mu$ connected with the changes of internal energy of the system gas-vacancy may be written as

$$\Delta\mu = \frac{1}{W}\,[(\mu_0^{gas}\,a - \mu_0^{*}\,a^{*}) + RT\,\ln p] \qquad (19)$$

where:

W – the size of adsorption volume, a and a* – number of moles of gas solution and vacancies, μ_0^{gas} and μ_0^* – chemical potentials of the gas and system vacancies in which adsorption volume is filled by vacancies, R – gas constant, T – temperature, p – concentration of gas phase at thermodynamic equilibrium.

Let us consider the case of isothermic transformation. For the system described by Eq. (17) the difference in free energy is described by

$$dF = -SdT - LdV + dE_{che} \tag{20}$$

where:

$$L = \sigma_{sur} - p - \frac{2\sigma_{sur}}{3\,(V)^{1/3}}$$

If dF = 0 and dT = 0 then

$$dE_{sur} = \frac{\underline{L_1\,(V_0 + \Delta V)}}{L_0 V_0} \tag{21}$$

and therefore the increase in the volume of a microblock or change in stress conditions (particulary in σ_{sur}) will, in accord with Eq. (9), depend on the thermodynamic conditions upon which the experiment is carried out, particulary on gas pressure.

VIII. DEFORMATION OF MACROPORE CHANNEL WALLS

The gas flow through coal matrix depends on permeability of the matrix. Permeability expresses the ability of the matrix to support the gas flow through pores and fissures. It depends on the tortuosity of hydrodynamic channels, openness of the fissures, undulation of the channel surface and number and position of constrictions which may block them.

The ratio of permeability of two channel systems k_0 and k may be expressed by equation (J. B. Walsh, 1981):

$$\frac{k}{k_0} = [1-2\,\frac{h}{a_0}\,\ln\,(\frac{p_e}{p_0})]^3\,[\frac{1 - b\,(p_e - p_0)}{1 + b\,(p_e - p_0)}] \tag{22}$$

where k_0, a_0, p_0 – initial permeability, fissure openness and pressure in the channels of the reference system, h – mean value of undulation of channel surfaces, p_e – side pressure, $p_s = (p_e - P_0)$ – effective pressure, b – tortuosity coefficient, where:

$$p_s = 1\,\frac{v_p\,\beta_s}{\delta v_p\,/\,\delta p} \tag{23}$$

where v_p –pore volume, β_s– compressibility of rocks enclosing the fissure [b – tortuosity, dependent on the form of channels].

If under the influence of factors described in Fig. 9 conditions that initiate shifts on the surfaces of channels arise, the energy evolved due to overcoming the forces of friction is also used for destruction of the complex structure of hydraulic channels. The flattening of channel surface results in decrease of coefficient S in Eq. (22), and this leads to a significant decrease of coefficient k in Eq. (22). On the other hand, high gas pessure increases the openness of fissures and also the decrease of coefficient k. The effect of permeability changes k resulting from shifts on the channel surface against the friction force, which are the source of seismoacoustic signals, may also explain the results of experiments presented in figure 8. This explanation presented may be corroborated by the results of experiments (Majewska, 1990) in which the sample was several times subjected to sorption and desorption of carbon dioxide. In subsequent stages of the sorption process different levels of seismoacoustic emission were recorded.

IX. THE EFFECT OF HYDROMECHANICAL PROCESSES IN A POROUS MEDIUM ON THE ACOUSTIC EMISSION

A porous medium filled with reservoir fluid, in a state of triaxial stress is subjected to stresses described by the following tensor:

$$\begin{Bmatrix} \sigma_{11}+p & \tau_{12} & \tau_{13} \\ \tau_{22} & \sigma_{22}+p & \tau_{23} \\ p_{31} & \tau_{32} & \sigma_{33}+p \end{Bmatrix} \qquad (24)$$

where σ_{ii} is principal stress, τ_{ij} is shear stress, and p is reservoir fluid pressure.

This notation (Eq. 24) points to a significant effect of pore pressure on the evolution of deformation processes in the rock-mass. In particular, the pressure change gives rise to non elastic deformations.

The yield point ϕ_α in a porous medium depends on a few factors. For instance, in the Mohr-Mises relation it is assumed that the following equation should hold at the yield point:

$$2/3\, H_r\sigma_r + \alpha\sigma_t - Y = 0 \qquad (25)$$

where σ_r is stress normal to the pore boundary, σ_t is stress tangential to the pore boundary, Y is the cohesion of the porous medium, α is the angle of internal friction, and

$$H_r = sig\,(\alpha_r - \alpha_t)$$

Deformations resulting from stresses applied to porous rock have the form:

$$de_{ij} = de^{e}_{ij} + de^{p}_{ij} \tag{26}$$

where de^{e}_{ij} is elastic deformation, and de^{p}_{ij} is non-elastic deformation related to dilatancy-elastoplastic deformation of a porous medium filled with reservoir fluid.

At the same time, the following relations hold:

$$\begin{aligned} de_{\gamma} &= de^{e}_{\gamma} + de^{p}_{\gamma} \\ de_{e} &= de^{e}_{n} + de^{p}_{n} \end{aligned} \tag{27}$$

where e and p are indicators of the elastic and non-elastic part of deformation, respectively, and indices γ and n refer to shear and normal stress, respectively.

$$\begin{aligned} de^{e}_{\gamma} &= d\sigma_r/G \\ de^{p}_{\gamma} &= \frac{(2/3)\, H_r\, d\sigma_r + \alpha\, d\sigma_t}{G} \\ de^{e} &= d\sigma_r\, K - dp/K^* \\ de^{p} &= \lambda de^{p}_{\lambda} \end{aligned} \tag{28}$$

where $K^* = K_l/K$, K being the elastic coefficient of bulk rock sample and K_l the elastic coefficient of the rock skeleton, and G is the coefficient of stiffness of rock samples. Parameter α describes the mechanical properties of roks or soil; it is sensitive to even a small amount of water occurring in rock.

The main effect of the presence of water is the decrease of the friction factor on the crack boundaries due to the decrease of Griffith's surface energy. Therefore, non-elastic deformation taking place inside a porous medium (and being the source of acoustic emission due to external stresses or due to pore pressure changes) gives rise to the changes of tensile strength near the crack boundary and as a result, its propagation.

In particular, the volume changes resulting from crack development may lead to changes of the hydraulic parameters. Assuming that the fluid is regulated by Darcy's law, the amount of fluid that flows through the porous medium is described by:

$$\bar{U} = -\frac{k}{\mu} \operatorname{grad} p \tag{29}$$

where U is the flow rate, μ is the coefficient of fluid dynamic viscosity, k is the permeability coefficient of the medium, and p is pressure.

Permeability of the porous medium depends on hydraulic radius of capillaries which are the channels of fluid flow and their density. The changes of mutual position of transporting canals resulting from non-elastic deformations, the increase of capillary density and, above all the increase of smoothness of canal surfaces crack sections provoke the violent increase in permeability of the medium as a result of differential stresses giving rise to plastic deformations.

It should be expected that the gradiet of hydraulic pressures in porous media induced the non-elastic deformations near the boundary of hydraulic canals which also become the source of acoustic emission.

At the same time, this gradient may cause a change of hydraulic permeability of the rock medium preceding the loss of seepage tightness.

CONCLUSIONS

The geophysical measurements are generally carried out for a spatial description distribution of the rock-mass physical parameters. The recording of acoustic emission from the rock-medium gives possibility to asses the dynamic process passing as a result of unelastic deformation. As it was shown, the development of external stresses may generate a cracked zone. Two parameters describing the zone seem to be important. One is a measure of interaction of the existing cracks which precede, the occurence, of cathastrophic changes in the rock state. The other is intensive changes in cracked zone fracture. Both of them may be estimated from records of acoustic emission.

The sorption, desorption of gases and liquids in porous rocks also give unelastic deformations which may be recorded with acoustic measuring system. This geophysical method may be used for assessment of the development of this thermodynamical and flow processes in rock-masses; it gives opportunity to control it and to predict its dangerous effects.

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