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STUDY OF THE AE FREQUENCY SPECTRA OF SOME ROCKS

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Results of investigation of the acoustic emission frequency spectra in sandstone, dolomite and marble samples under uniaxial incremental compressive load are presented. The measurements of AE peak hold spectra within each incremental loading cycle in frequency range from 100 Hz–100 kHz, and averaged over 30 s interval spectra in the range from 5 kHz to 100 kHz, were made.

It was found that for nonhomogeneous rocks i.e. sandstone and dolomite the dominant frequency bands shifted towards higher frequencies with the increase of load. Prior to failure of these samples, the increase of low frequency components was observed. For the marble (carrare) which has more homogeneous structure the spectra were less differentiated and their evolution less pronounced.

The results obtained support the hypothesis of stress concentration on limits of the defects in regions of eventual failure planes. The observed increase of low frequency components could be used in practice in the prediction of failure of heterogeneous rocks.

W pracy przedstawiono wyniki badań widma częstotliwości emisji akustycznej próbek: piaskowca, dolomitu i marmuru, w funkcji jednoosiowych obciążeń ściskających, wzrastających skokowo. Wykonano pomiary maksymalnych gęstości widmowych AE, procedurą „peak hold", dla każdego cyklu obciążenia w zakresie częstotliwości 100 Hz–100 kHz oraz widm uśrednionych w czasie 30 s, w zakresie 5 kHz – 100 kHz.

Stwierdzono, że dla skał niejednorodnych: piaskowców i dolomitów LGOM, zakresy widma o maksymalnych gęstościach amplitudy przesuwały się ze wzrostem obciążenia w kierunku dużych częstotliwości. Bezpośrednio przed zniszczeniem tych skał obserwowano wzrost składowych o małych częstotliwościach. Dla marmuru (carrare), o jednorodnej strukturze, widma były mniej zróżnicowane a ich ewolucja mniej wyraźna.

Otrzymane wyniki badań potwierdzają hipotezę o koncentracji naprężeń na powierzchni wad, w strefach przyszłego zniszczenia. Obserwowany wzrost składowych o małych częstotliwościach może być wykorzystany w praktyce do przewidywań rozpadu skał niejednorodnych.

1. Introduction

The evolution of acoustic emission has been used in investigation of structure and of mechanical failure process of rock subjected to external stress. The present work has been aimed at the investigation of the AE accompanying the fracturing process of some rocks: dolomite, sandstone and marble, under uniaxial compression leading to failure. Specifically the AE frequency spectra evolution of these rocks were investigated, and found to provide significant information pertaining to the nature of fracturing process. The available experimental data on the AE frequency spectra evolution during the deformation of rocks indicate, that the observed shift towards low or high frequencies with increasing stress, remains open to question. Chugh et al., Kusunose et al., Ohnaka and Mogi and also Reymond [1, 7, 8, 9, 10, 12, 13], examined the AE frequency spectra of the rocks under uniaxial incremental load, however, their observations were not fully consistent.

One of the first general studies on the AE frequency spectra belonging to classics but still of importance today, was published by Chugh et al. [1]. The subject of investigation was the AE frequency spectra of a limestone, sandstone and granite samples under increasing tensile stress in the frequency range between 0.5 and 15.0 kHz only. The results of this work could be summarized as follows:

– each of the examined rocks was characterized by one or several dominant frequency bands (DFB) in which the most of AE energy was generated.

– for high stresses, the energy of acoustic emission increased in the range of higher frequencies.

Kusunose et al. [7] studied the AE in granite samples under uniaxial compression in the range of frequencies from 100 kHz to 1 MHz. The comparative analysis of the most pronounced AE amplitudes in 5 μs intervals and frequency ranges: from 100 to 400 kHz and from 500 kHz to 1 MHz, indicates, that in accordance with the theory given in their work, waveforms of acoustic emission were more abundant in high frequency components as the applied stress increased.

Ohnaka and Mogi [8, 9, 10] carried out the comparative analysis of the AE event rate monitored through the windows of different frequency bands in the range from 10 kHz to 2 MHz. They observed the increased low frequency AE event rate with incrementally increased load and, immediately before and during the sample's failure, the increased high frequency AE event rate. In case of the application of constant load (creep test) the increased low frequency AE event rate as a function of time up to failure was observed.

The works by Reymond [11, 12, 13] were concerned with examination of the AE frequency spectra of some rocks (e.g. limestone) as a function of incrementally increased compression, in the range from 100 Hz to 20 kHz. The results obtained show, that the maximal spectrum density shifts towards high frequencies as the load applied is increased. As the rock approached failure, very high spectral density was observed in the whole frequency range to decrease immediately prior to the failure, particularly in the range of very high frequencies.

Evolution of dominant spectral density was also a subject of numerous investigations with reference to earthquake prediction. The results of these investigations have significant general value on account of the scale invariable character of the fracture process of rocks under external stresses.

FEDOTOV et al., ISHIDA et al. and UTSU [2, 4, 16], obtained contradictory results in this respect. Investigations by ISHIDA and by UTSU indicate, that the foreshocks prior to earthquake, i.e. so called precursors, are characterized by frequency spectra shifted towards higher frequencies relative to the earlier events. On the contrary, FEDOTOV et al. [2] observed the shift of spectral components towards low frequencies immediately prior to a large earthquake.

SALA [14], in his works on AE, assumed that elastic wave generation in the rocks subjected to deformation, in cases of their elasto – brittle behaviour, is identical with earthquakes within the crusts of the earth which exhibit substantial tectonic stresses.

In accord with the results of granite investigation under indirect tensile stress (brasilian test), a shift of the dominant AE spectra components from low to high frequencies, up to the stress approaching strength, followed by the increase of low frequency components, was observed. In case of AE spectra measurements of granite under compressive stress, the results exhibit analogous evolution of the spectra however, the last phase of this evolution occuring earlier and being more pronounced.

In the present work cumulative results of the AE investigation in rocks carried out within the Polish-French scientific cooperation are given. This investigation were aimed, among others, at the analysis and the estimation of AE spectral width of some rocks and at its evolution as a function of uniaxial, incremental compression. Subjected to this investigation were samples of sandstone and dolomite from Legnica-Glogow Copper District in Poland and of marble (carrare) from France.

Spectral analysis of the AE in some samples and the measurements of their physical parameters were performed in France. To these authors knowledge no data were published, in the two countries, with reference to the spectral analysis of the AE in brittle rock, in the range of frequencies up to 100 kHz, under uniaxial compression.

2. Experimental Procedure

Cylindrical specimens of the examined rock, measuring 60 mm in length and 30 mm in diameter, were subjected to uniaxial compressive load until fracture occured, using large hydraulic press. The load was varied incrementally in the following way: very slow 1 tone increment of load was used and kept constant over a period of 3 to 14 min duration. Prolongation of that period over 3 min was used only in cases of observable acoustic activity and was kept until it ceased.

Test specimens were measured also with reference to their physical parameters such as elastic longitudinal wave velocity in samples dry and in samples water saturated, mass density, bulk density and porosity. These parameters and the samples' compressive strength are give in Table 1.

Table 1

Rock type sample number	Longitudinal wave velocity c_p m/s	Longitudinal wave velocity (water saturated) c_{ps} m/s	Bulk density ϱ_v g/cm²	Mass density ϱ g/cm²	Porosity p %	Compressive strength σ_r MPa
Sandstone P1	3200	3150	2.13	2.71	21.3	31.1
Sandstone P2	3560	3370	2.25	2.69	16.1	83.37
Sandstone P3	4460	4040	2.42	2.74	11.8	111.16
Dolomite D1	6000	5630	2.67	2.72	1.8	152.8
Dolomite D2	5910	6030	2.71	2.73	0.6	127.3
Dolomite D3	6000	6050	2.71	2.72	0.5	194.5
Marble C1	3880	5190	2.70	2.71	0.3	86.3
Marble C2	3730	5190	2.70	2.71	0.3	111.16
Marble C3	3730	5260	2.70	2.71	0.3	111.16

In order to detect the AE during loading, a Bruel and Kjaer type 4344 piezoelectric accelerometer was cemented to one side of the examined cylindrical specimen. The accelerometer frequency response was: 2Hz to 100 kHz.

The amplified waveforms were fed to a wide band (100 Hz to 150 kHz) magnetic tape recorder. The frequency spectra of the recorded AE events were analysed using the Fast Fourier Transform. To obtain maximum spectral density, within each incremental loading cycle a peak hold procedure was used.

3. Results

The AE peak hold frequency spectra for the sandstone samples at 0.16 and 0.90 of the failure stress are shown for illustration in Fig. 1. Detailed analysis of the results obtained shows, that for loads below 0.16 of the failure stress, a pronounced domination of low frequency components (up to approx. 10 kHz) is observed. As the load is increased, a shift of the dominant frequency bands towards higher frequencies is observed.

Peak hold spectra for the dolomite samples also shows domination of low frequency components below 0.14 of the failure stress. For higher loads the dominant frequency bands shifted in the direction of higher frequencies, amounting 70 to 90 kHz for 0.90 of the failure stress. For illustration of the AE spectrum evolution, the representative spectra for 0.14, 0.57 and 0.92 of the failure stress for dolomite samples, are given in Fig. 2.

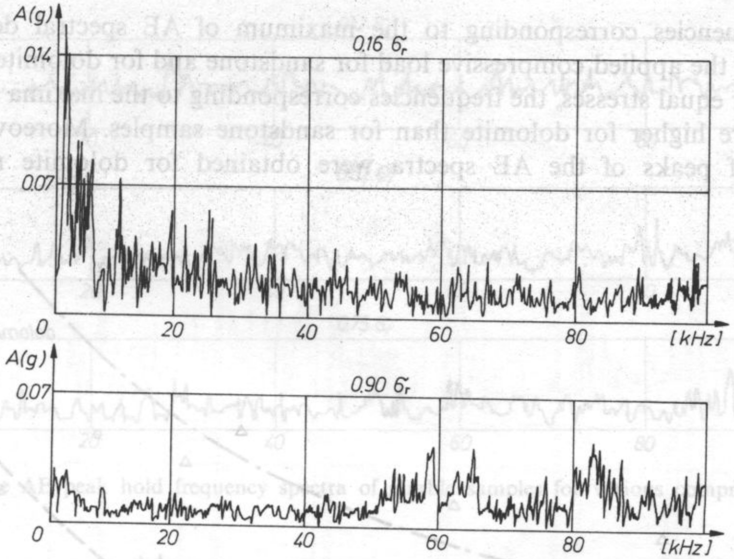

FIG. 1. The AE peak hold frequency spectra of sandstone samples for various compressive stresses

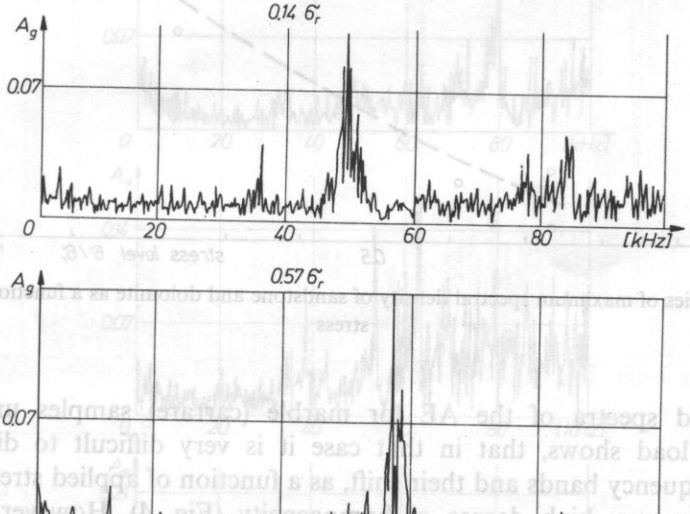

FIG. 2. The AE peak hold frequency spectra of dolomite samples for various compressive stresses

The frequencies corresponding to the maximum of AE spectral densities as a function of the applied compressive load for sandstone and for dolomite are given in Fig. 3. For equal stresses, the frequencies corresponding to the maxima of spectral densities were higher for dolomite than for sandstone samples. Moreover, higher amplitude of peaks of the AE spectra were obtained for dolomite relative to a sandstone.

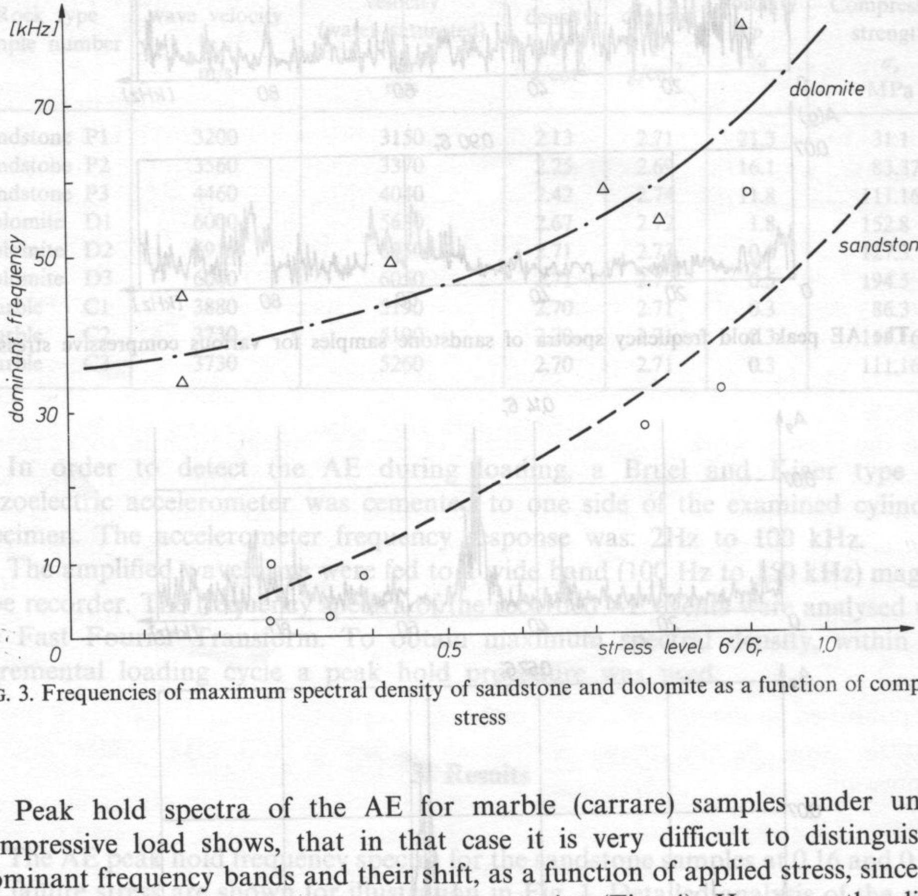

FIG. 3. Frequencies of maximum spectral density of sandstone and dolomite as a function of compressive stress

Peak hold spectra of the AE for marble (carrare) samples under uniaxial compressive load shows, that in that case it is very difficult to distinguish the dominant frequency bands and their shift, as a function of applied stress, since these samples show very high degree of homogeneity (Fig. 4). However, the discrete maximum of spectral density, shifting in the direction of higher frequencies i.e., from 28 kHz for 0.12 of the failure stress to 89 kHz for 0.75 of the failure stress, as the applied stress increased was observed.

Within a few minutes prior to the failure of a sample it was found that, for the sandstone and the dolomite samples examined, a shift of the dominant frequency bands to low frequencies occured. The domination of low frequency components in the AE spectrum at relatively high load indicates, that the process leading to failure of a sample is initiated. This phenomenon is illustrated by the AE peak hold spectra for sandstone and dolomite a few minutes prior to the failure, given in Fig. 5 and Fig. 6.

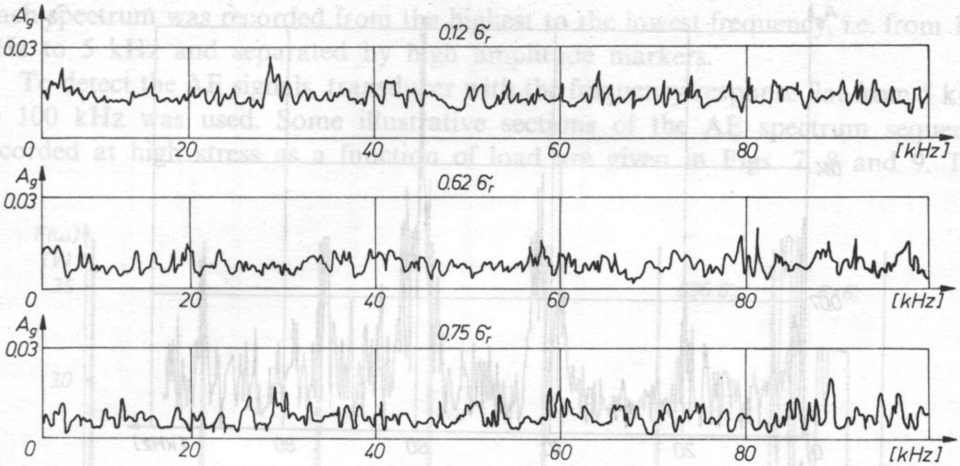

FIG. 4. The AE peak hold frequency spectra of marble samples for various compressive stresses

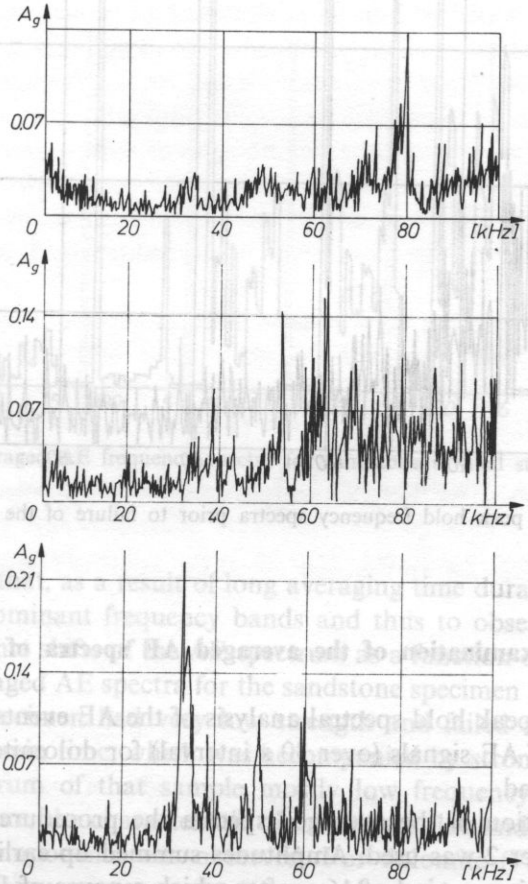

FIG. 5. The AE peak hold frequency spectra prior to failure of the sandstone sample

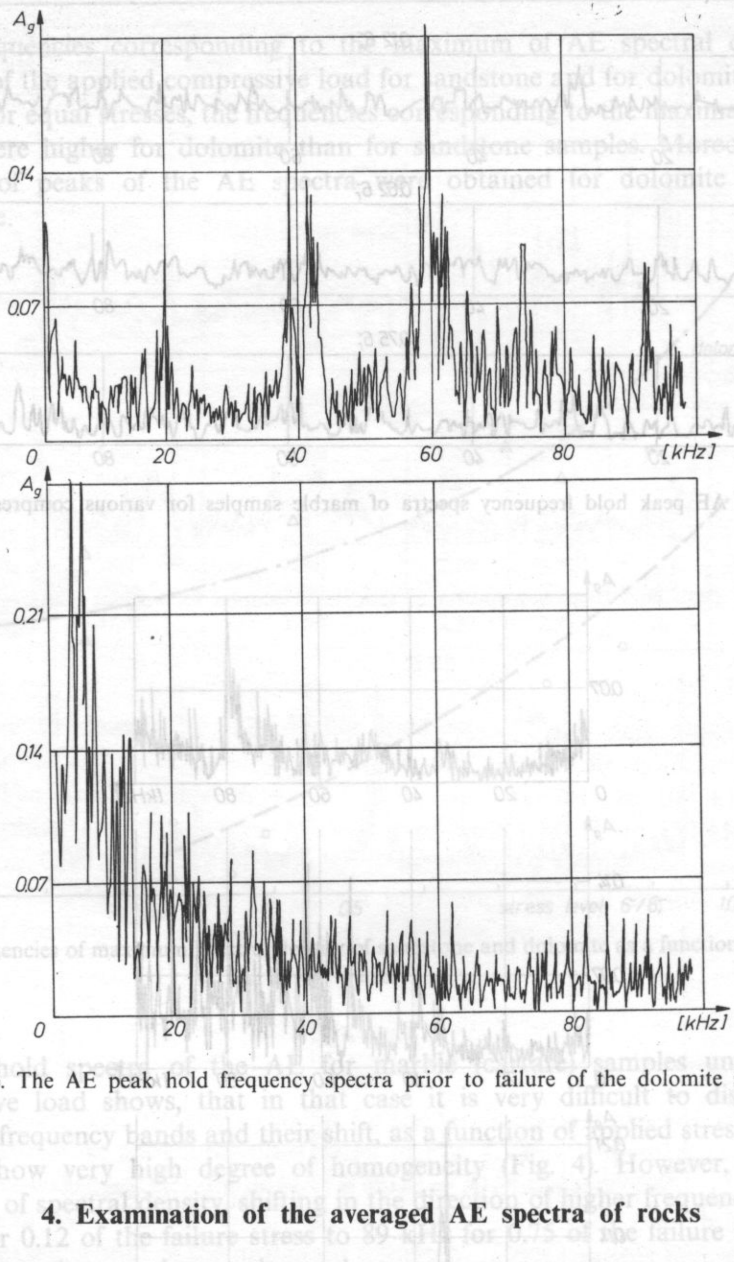

FIG. 6. The AE peak hold frequency spectra prior to failure of the dolomite sample

4. Examination of the averaged AE spectra of rocks

Along with the peak hold spectral analysis of the AE events, examination of the averaged spectra of AE signals (over 30 s interval) for dolomite and sandstone was performed in Poland.

In the examination of the averaged spectra the procedure of load application described in Chapter 2 was used. Amplitudes summed up earlier over 30 s interval are registered in a time period of 16 s, after which a pause of 14 s duration follows.

Each spectrum was recorded from the highest to the lowest frequency, i.e. from 100 kHz to 5 kHz and separated by high amplitude markers.

To detect the AE signals, transducer with the frequency response flat from 5 kHz to 100 kHz was used. Some illustrative sections of the AE spectrum sequence recorded at high stress as a function of load are given in Figs. 7, 8 and 9. The obtained data show that, as a result of long averaging time duration, it was difficult to distinguish the dominant frequency bands and thus to observe their evolution. However, some distinct shifts of the AE spectrum as a function of time was noticed.

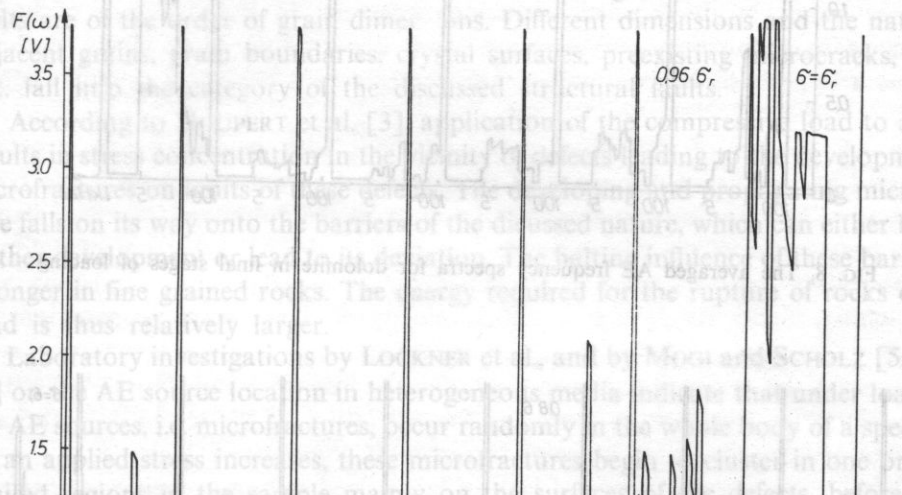

FIG. 7. The averaged AE frequency spectra for sandstone in final stages of loading

Some of the averaged AE spectra for the sandstone specimen P1 are given in Fig. 7. This particular specimen had very low strength and failed at constant load of 2 tones in approx. 6 min time, which was accompanied by strong acoustic activity.

In the AE spectrum of that sample mostly low frequency components were present. Prior to failure, the characteristic obtained was flat, and next a domination of high frequency components was observed. For dolomite (Fig. 8), a growth of amplitudes of high frequency components was observed at approximately 0.7 of

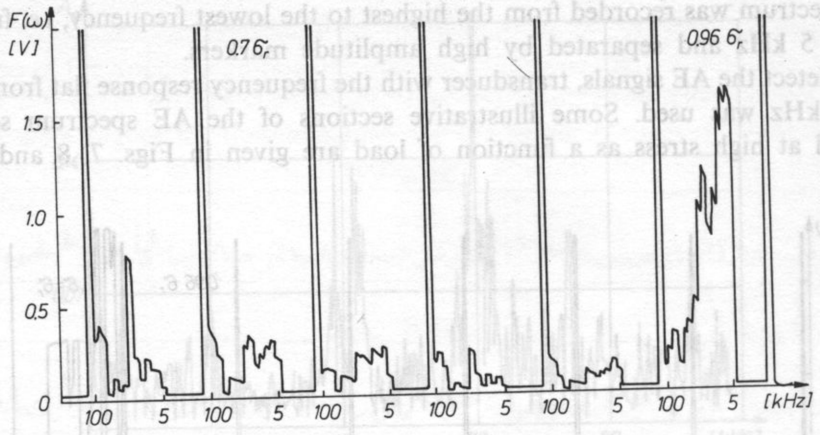

FIG. 8. The averaged AE frequency spectra for dolomite in final stages of loading

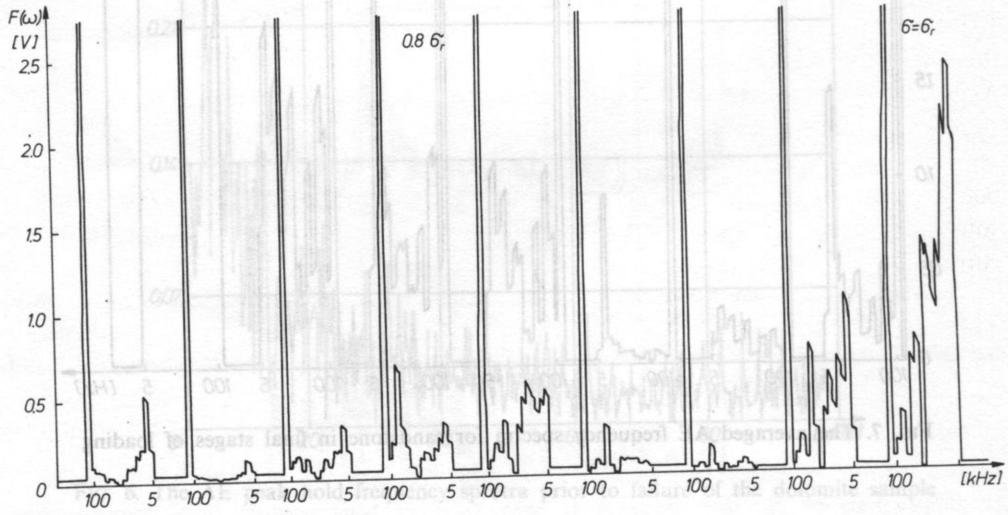

FIG. 9. The averaged AE frequency spectra for marble in final stages of loading

failure load, and next a considerable domination of amplitudes of low frequency components, prior to failure i.e. for 0.96 of failure load.

For marble (Fig. 9), also a growth of amplitudes of high frequency components was found for 0.8 of failure load, and next their diminution and growth of amplitudes of low frequency components immediately prior to failure. The obtained data indicate, that the evolution of the averaged AE signals is not fully consistent with the AE peak hold spectra evolution only in the case of sandstone samples.

5. Discussion and Conclusions

Process of the development and propagation of microfractures under external stresses, which lead to the inelastic deformation of rock and to the generation of acoustic waves, results in failure of brittle rocks. Rocks generally have large number of structural defects like discontinuities and unhomogeneities. Dimensions of these faults are of the order of grain dimensions. Different dimensions and the nature of adjacent grains, grain boundaries, crystal surfaces, preexisting microcracks, pores, etc., fall into the category of the discussed structural faults.

According to Houpert et al. [3], application of the compressive load to a rock, results in stress concentration in the vicinity of defects leading to the development of microfractures on limits of these defects. The developing and propagating microfracture falls on its way onto the barriers of the dicussed nature, which can either halt its further development or lead to its deviation. The halting influence of these barriers is stronger in fine grained rocks. The energy required for the rupture of rocks of that kind is thus relatively larger.

Laboratory investigations by Lockner et al., and by Mogi and Scholz [5, 6, 11, 15] on the AE source location in heterogeneous media indicate that under load first the AE sources, i.e. microfractures, occur randomly in the whole body of a specimen. As an applied stress increases, these microfractures begin to cluster in one or more limited regions in the sample mainly on the surfaces of the defects, before stress approaching failure, whilst acoustic activity of the remaining sources decreases. Just before rupture the microfractures in one of the most active regions develope, at sufficiently large local concentration of stress, to result in the main macroscopic rupture.

The results of investigations by Kusunose et al. [7] are of particular significance. They have shown that the local drop of dynamic stress, resulting from the development of microfractures, in the range of low loads, is proportional to the external stress. For stresses in excess of 85% of ultimate strength however, this drop is significantly larger than the external stress. This observation implies that the degree of stress concentration is unproportionally higher for higher external loads.

This dependency was confirmed experimentally by Kusunose et al. [7] on the grounds of the observed enlargement of high frequency components in the AE waveforms for high loads. It was also shown that the propagation effect is not responsible of the spectrum shift i.e. that the frequency dependence of attenuation of acoustic waves does not contribute in the AE spectrum evolution as a function of load.

Concentration of sources of seismoacoustic signals in the region of rock mass fractures was observed also by Zuberek [17] in coal mines.

Ishida et al. [4] observed that in a time period preceding large earthquakes, a significant concentration of a foreshock seismic activity, which has form of small earthquakes, occurs around the future epicenter. It is characterized by consistently higher frequencies of peak spectral components in comparison with ordinary events. This fact seems to support a hypothesis of high progressive stress concentration leading to the development of rock mass fractures and consequently to the significant local drop of dynamic stress.

Reconsidering the results of investigations cited, it can be assumed, that frequency spectrum of the AE event depends: on stress in the region of the AE source, on dimensions of the AE source; on a structure (degree of heterogeneity) of rock medium and on the AE source mechanism. Evolution of the dominant frequency bands in the acoustic emission spectrum, in the direction of higher frequencies as a function of increasing load, observed by the present authors, confirms a hypothesis of local stress concentration in a region of eventual failure plane.

The AE spectra of dolomites and sandstones with heterogeneous structure, manifested by significant dispersion of their physical parameters given Table 1, are characterized by large amplitude spectral density in the dominant frequency bands. Higher frequencies of the dominant components in the AE spectrum of dolomite seem to result from its more fine grained structure relative to sandstone and, consequently, higher strength and higher velocity of elastic wave propagation, see Table 1.

In general, the obtained data point out, that the frequency range up to 100 kHz is representative for spectrum evolution of the AE events of the tested dolomite and sandstone specimens, under uniaxial incremental compressive load.

In marble, as a consequence of lack of large sized unhomogeneities, microfractures develop in a minor degreee immediately prior to failure. On account of lack of occurrence of the considerable stress concentrations as well as microfractures, only the evolution of the discrete maximal spectral components of small density is observed, which is in favour of the hypothetically assumed mechanism. However, pronounced evolution of the AE long time average spectra is observed.

A very rapid growth of amplitude density of low frequency spectral components, immediately before failure of the majority of dolomite and of sandstone specimens, indicates the initiation of macroscopic fracture. The development and propagation of microfractures in the vicinity of the more strong defect, leads to rapid growth of the eventual failure plane. Generation of larger cracks occurs and/or coalescence of minor cracks into larger cracks takes place, leading to macroscopic failure. In that way the average size of the AE sources increases. Larger sources of the AE tend to generate AE events containing lower frequency components.

It seems that the shift of dominant frequency bands towards lower frequencies could be used as an indication of significant value in the prediction of failure of heterogeneous rocks. For final conclusion however, investigation of the AE spectra for large population of test specimens and statistical analysis of data are necessary.

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