ARCHIVES OF ACOUSTICS
15, 3-4, 311-324 (1990)

DEPENDENCE OF THE AE MAXIMUM BURST AMPLITUDE ON THE DEFORMATION MECHANISM IN SOME ROCKS

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Maximum amplitude of acoustic emission events in 10 second intervals were measured in the samples of dolomite and sandstone under uniaxial compressive load.

The observed sudden increase of the maximum amplitude, in a function of load, indicates the beginning of the unstable propagation of microfractures, leading to uncontrolled failure of a sample. The maximum amplitude dependence on load, as directly related to the AE source mechanism, can be used in prediction of the rock damage in situ.

Przedstawiono wyniki badań maksymalnej amplitudy emisji akustycznej w interwałach 10-sekundowych, próbek dolomitu i piaskowca, poddawanych jednoosiowym naprężeniom ściskającym. Obserwowany znaczny wzrost maksymalnych amplitud, w funkcji czasu obciążania, wskazuje na rozpoczęcie się propagacji niestabilnej mikropęknięć, które prowadzą do niekontrolowanego zniszczenia próbki. Przebieg maksymalnej amplitudy sygnałów w funkcji obciążeń, jako zależny bezpośrednio od mechanizmu źródła EA, może być wykorzystywany do przewidywania rozpadu skał in situ.

Acoustic emission (AE) used in non-destructive testing of objects and constructions as well as materials, e.g. metals and composite materials, or in testing of leak-proof objects as well as in the localization of leakages, has been almost generally accepted and is recommended by the corresponding standards. It is also used in the industry. However, the use of the AE methods in assessment of stability of rocks in situ, on account of their heterogeneous structure, requires still further studies.

The reported results of investigation in this respect [1–8] indicate that the AE maximum burst amplitude is one of the most representative parameters of acoustic emission observed in brittle rocks under load, since its value depends directly on the AE source mechanism. A sudden increase of maximum amplitudes indicates the beginning of the unstable or semistable fracture propagation which leads to an uncontrolled rupture. Also, the results of measurements of the AE maximum burst amplitude are relatively the less dependent on the technical data of the equipment used and on the dimensions of samples tested. A theoretical pulse signal of the AE event, and its maximum amplitude A_m as a function of time is shown in Fig. 1.

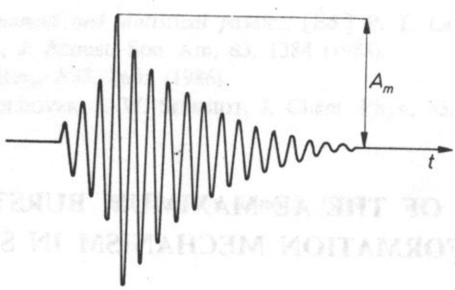

FIG. 1. Theoretical plot of pulse signal – AE event

Most works pertaining to the maximum amplitude of the AE signal in rocks were aimed at a characteristic maximum amplitude/event number statistical destribution, [8–10]. The results obtained show that this distribution obeyed in many cases, for some loading range, Ischimoto-Iida distribution well known in seismology:

$$n(a)da = ka^{-m}da, \tag{1}$$

where: $n(a)$ – number of signals with amplitudes in the range between: $a+da$ and $a-da$, a – maximum signal amplitude, k and m – constants.

Investigation of the exponent m as a function of load has shown, that the rock burst prediction on the grounds of its (i.e. m exponent) changes is possible for brittle rocks characterized by un unexplosive rupture and also for quasi-brittle rocks. However, such a prediction is impossible for ductile rocks [8].

In the present work, investigation of the AE maximum burst amplitude under uniaxial compression, in samples of some rocks from Legnica-Glogow Copper District was carried out. The results of the AE maximum burst amplitude measurements presented in this paper were obtained with the use of a modified measurement procedure. In this procedure, the measurement of the maximum burst amplitude as a function of compressive load was taken in 10s time intervals. Both, the procedure as well as the equipment used in its execution were simplified in a substantial degree. The results obtained are quite easy to interprete and, as it seems, could be recognized as good grounds for positive prognosis with regards to the utility of the method.

1. Measurements of samples

For the measurements of the AE maximum burst amplitude, 21 cylindrical samples of dolomite (dolomitic-limestone) and sandstone from the Legnica-Glogow Copper District were used. The diameter to length ratio in this samples was 0.5.

Prior to the measurements of AE, some physical and mechanical properties of the samples were determined. In Table 1 sample dimensions, travel times for elastic longitudinal t_p and transveral t_s waves, longitudinal c_p and transveral c_s wave velocities and their compressive strengths σ_r, obtained in the next part of experimental work, for dolomite samples are given. In Table 2 the same properties for the

Table 1. Results of ultrasonic measurements of cylindrical dolomite samples from Legnica-Glogow Copper District

No. of sample	Dimensions l [mm]	$\varnothing$ [mm]	t_p [μs]	c_p [m/s]	t_s [μs]	c_s [m/s]	σ_r [MPa]	Remarks
1	60.0	30.0	12.9	4651	22.6	2655	56.6	
2	61.0	30.0	10.5	5810	18.7	3262	84.9	
5	69.0	30.0	21.7	3180	36.4	1896		
6	68.7	30.0	17.8	3860	30.3	2267		
7	62.0	30.0	15.3	4052	25.9	2394	70.7	
8	60.0	30.0	15.7	3822	27.3	2198	77.8 92,0	sample divided in two parts
10	60.0	30.0	13.7	4380	23.9	2510	70.7	
12	62.0	30.0	10.0	6200	18.1	3425	53.8	
13	63.0	30.0	12.8	4922	22.6	2788	84.9	
15	63.5	30.0	15.7	4045	27.4	2318	42.4	fractured
17	60.0	30.0	9.9	6061	17.8	3370	56.6	
19	60.0	30.0	11.0	5455	19.5	3077	103.3	
20	85.5	42.0	13.6	6287	24.5	3490	65.0	
21	85.5	42.0	13.6	6477	24.2	3533	115.5	
22	85.8	43.0	13.6	6173	25.5	3365	117.1	

Table 2. Results of ultrasonic measurements of cylindrical sandstone samples from Legnica-Glogow Copper District

No. of sample	Dimensions l [mm]	$\varnothing$ [mm]	t_p [μs]	c_p [m/s]	t_s [μs]	c_s [m/s]	σ_r [MPa]	Remarks
3 p	64.0	30.0	19.0	3368	31.0	2065	14.2	
5 p	46.0	30.0	17.9	2570	28.8	1597	18.4	fractured
7 p	60.0	30.0	38.5	1558	59.7	1005	21.2	fractured
9 p	63.0	30.0	26.2	2405	41.9	1504	22.6	
10 p	96.0	47.0	53.1	1808	83.4	1151	64.9	
11 p	96.0	48.0	47.5	2021	76.0	1263	78.8	

sandstone samples are given. The measurements of elastic wave velocities were carried out at frequency 200 kHz.

The results of measurements of mass density, bulk density, porosity and absorbability of all the samples and information concerning their lithology are given in Table 3. The observed dispersion of presented data indicates substantial heterogeneity of the rocks tested.

The samples were divided into groups characterized by similarity of the physical and mechanical data given in Tables 1,2 and 3.

Table 3. Results of measurements of mass density ϱ_m, bulk density ϱ_v porosity p and absorbability n of samples tested

No of sample	Rock type	ϱ_m [Tm^{-3}]	ϱ_v [Tm^{-3}]	p [%]	n [%]	Remarks
1	2	3	4	5	6	7
1	fine grained dolomitic limestone	2.77	2,69	2.9	0.7	
2	fine grained dolomitic limestone	2.79	2,69	3.6	0.1	
3 p	fine grained sandstone	2.65	2.22	16.2	—	
5	fine grained limestone	2.82	2.65	6.0	1.7	
5 p	fine grained sandstone	2.77	2.46	11.2	4.0	
6	fine grained limestone	2.75	2.54	7.6	1.0	
7	fine grained limestone	2.84	2.68	5.6	0.9	
7 p	fine grained sandstone	2.65	3.39	9.8	5.4	
8	fine grained dolomitic limestone	2.87	2.72	5.2	0.9	
9 p	fine grained sandstone	2.65	2.50	5.7	1.6	
10	fine grained dolomitic limestone	2.88	2,70	6.2	1.0	
10 p	fine grained powdery sandstone	2.70	2,28	15.5	—	
11 p	fine grained powdery sandstone	2.70	2,28	15.5	—	
12	fine grained dolomitic limestone	2.86	2,74	4.2	0.1	

1	2	3	4	5	6	7
13	fine grained dense dolomitic limenstone	2.87	2,65	7.7	1.3	
15	fine grained dolomitic limestone	2.75	2,61	5.1	0.8	
17	fine grained dolomitic limestone	2.84	2,74	3.5	0.1	
19	coarse grained dense dolomitic limenstone	2.86	2,76	3.5	0.1	
20	fine grained dense dolomitic limenstone	2.93	2,81	4.1	–	
21	fine and average grained dolomite	2.90	2,76	4.8	–	
22	fine grained dolomitic limestone	2.88	2,62	9.0	–	

2. Measurement of the AE maximum burst amplitude and even rate

The described rock samples were tested under uniaxial compressive load exerted by hand operated hydraulic press. The AE maximum burst amplitude was measured in 10s time intervals and registered by x–y plotter and digitally. The results of measurements of the AE event rates were registered in 1s intervals using x–y plotter and digitally in 10s.

Acoustic emission measurements were carried out at/for

1. various loading rates,
2. various frequency ranges,
3. various sample dimensions.

As a receiver of AE signals, a piezoelectric transducer with flat (within $\pm$ 3dB) frequency response in the range 1.5–150 KHz, was used. This transducer was cemented to the side wall of cylindrical samples used.

3. Results of measurements

For the majority of samples a plot of the AE maximum burst amplitude, with increasing load, was in agreement with a plot of event rate which is well manifested in the sample No 19. In Fig. 2 a plot of its AE maximum burst amplitude A_m in 10s

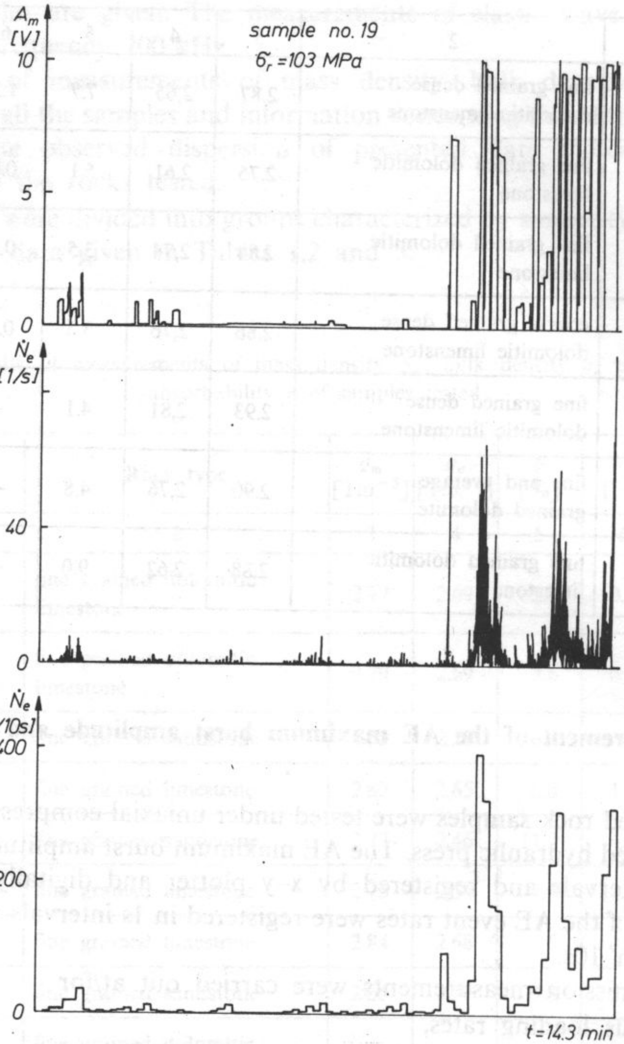

FIG. 2. AE maximum burst amplitude A_m in 10s (upper) and event rate $\dot{N}_e$ in 1s and 10s (lower) for sample No 19 as a function of loading time t

intervals (upper plot) and the event rate in 1s intervals and 10s intervals (lower plot) is given as a function of loading time t.

However, in some samples a sudden increase of the maximum amplitudes was observed, while the level of event rates was quite small and remained almost unchanged e.g. in samples No 2 and No 7 (Fig. 3 and Fig. 7). Since, it must be observed that the increase of event rate not always is a sufficient indicator to signal a beginning of sample failure and therefore cannot be used explicitly in the prediction of rock burst.

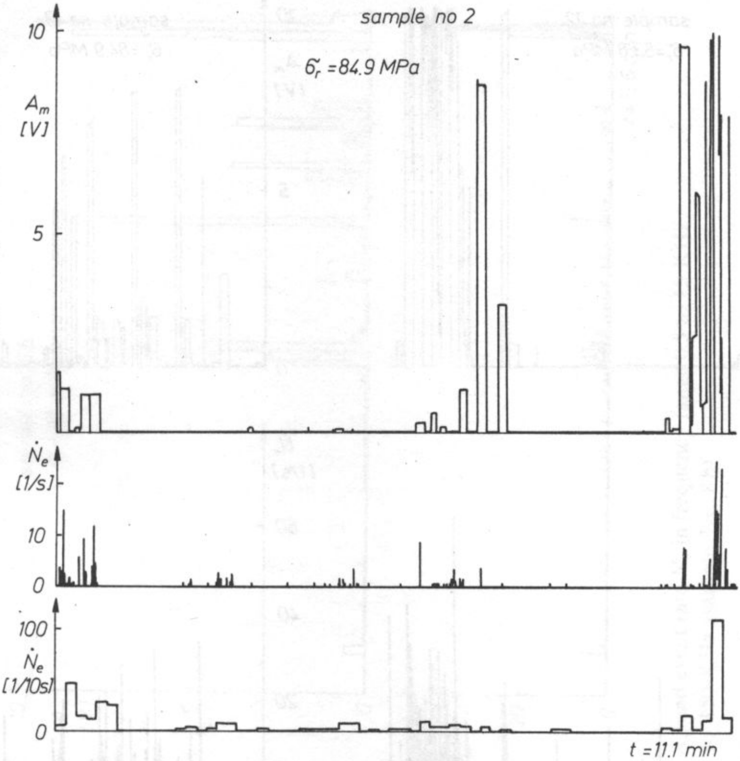

FIG. 3. AE maximum burst amplitude A_m plot in 10s (upper) and event rate N_e in 1s and 10s (lower) for sample No 2

In investigation of the influence of load rate on the acoustic emission in rock, two different sample loading procedures were used. Some samples were loaded at a rate of 14 MPa/min, other samples were loaded incrementally i.e. increment of load 14 MPa/min was used and was kept constant in a period of 1 min. The linear or incremental load was increased until failure. The measurements of acoustic emission as dependent on the rate of sample loading were performed in the frequency range from 1.5 to 150 KHz.

The results obtained show that at slow loading rate (incremental) of the samples, more small amplitude events is observed since fractures propagate at a lower velocity, and dimensions of the AE sources are smaller, e.g. sample No 12 (Fig. 4). At a faster loading rate, the events of larger energy are observed and the rock failure process is quicker, e.g. sample No 13 (Fig. 4).

In the AE investigation, also the influence of the frequency response of the AE channel on the plot of AE maximum burst amplitude and event rate was examined. The measurements of AE of some samples were performed in a low frequency range i.e. 0.5–15 KHz and for some other samples in a higher frequency range i.e. 15–150 KHz. In these cases the load was increased incrementally.

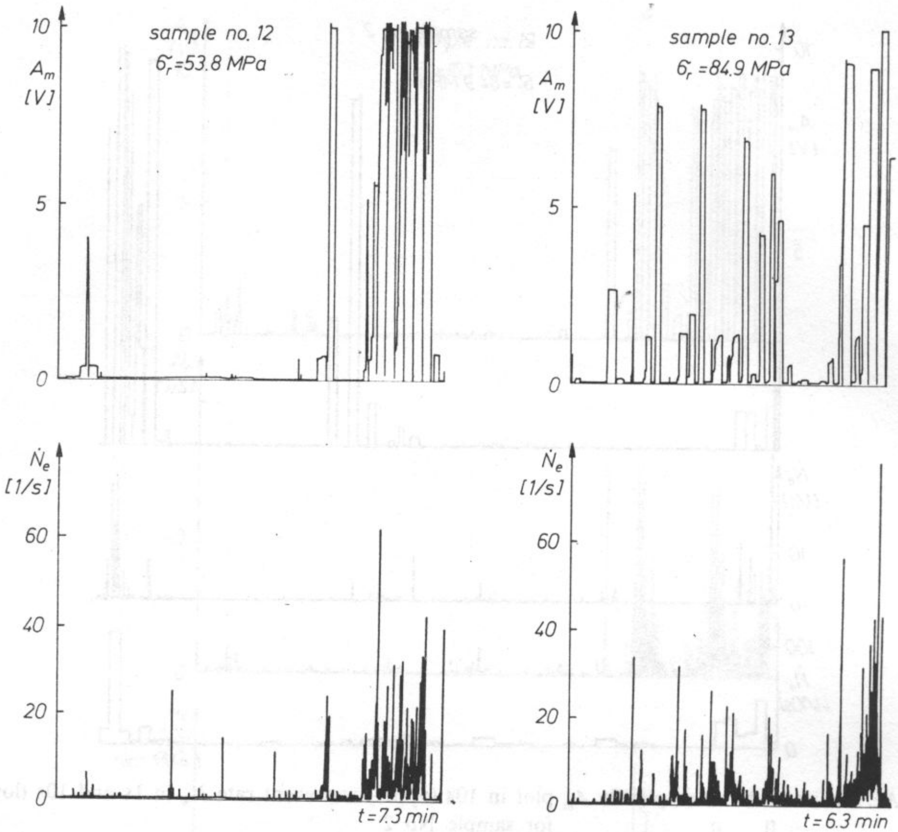

FIG. 4. AE maximum burst amplitude A_m plot in 10s and event rate N_e in 1s as a function of incremental loading (sample No 12) and linear (sample No 13)

Summarizing, the results obtained indicate that for dolomite higher maximum amplitudes were observed in the low frequency range (0.5–15 KHz), e.g. sample No 8a. However, the event rates in this range were smaller than in the high frequency range (15–150 KHz) e.g. sample No 8b (Fig. 5). The samples No 8a and No 8b were obtained by dividing the sample No 8 into two separate equal parts.

For sandstone, higher values of maximum amplitudes as well as event rates were observed in the low frequency range. These results indicate that the sandstone AE frequency spectrum is shifted downwards relative to the AE frequency spectrum of dolomite, and are in good agreement with the measurements of the AE spectra for these rocks [7].

No significant influence of sample dimensions on the character of maximum amplitude and event rate under compressive load, for the rocks tested, was observed. However, higher event rates were observed in the samples of larger dimensions.

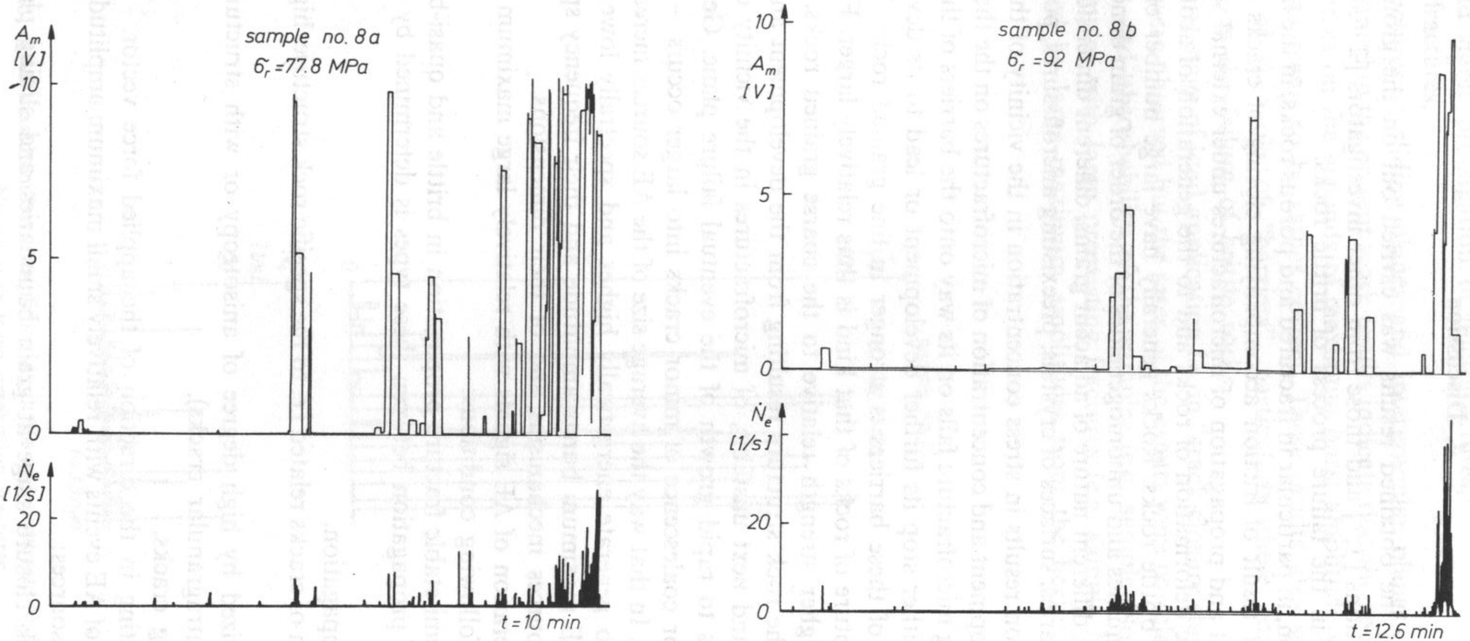

FIG. 5. The plot of AE maximum burst amplitude A_m and event rate N_e in frequency range 0.5 to 15 KHz (sample No 8 a) and 15 to 150 KHz (sample No 8 b)

4. Discussion

Interpretation of the obtained results was carried out on the grounds of the earlier own observations [1,7] and those from other investigators [2–5, 8–10] both relating to the AE in the failure process of brittle rocks.

Acoustic emission, in particular in fractured and porous rocks, in the first stage of loading occurs as a result of friction accompanying closing of cracks and pores.

The development and propagation of microfractures under external stress which leads to the inelastic deformation of rocks 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 of the order of grain dimensions. To this class belong e.g. different nature of adjacent grains, different dimensions of these grains, grain boundaries, surfaces of crystals, preexisting microfissures, pores and the like. Load application results in stress concentration in the vicinity of these defects, leading to the development and concentration of microfractures on the their surfaces.

The propagating microfracture falls on its way onto the barriers of the discussed nature which can either stop its further development or lead to its deviation. The stoppage 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. Fine grained rocks have thus higher strength relative to the coarse grained rocks.

Weakening of the rock structure resulting from the development and propagation, firstly stable and next unstable, of microfractures in the vicinity of the most strong defects leads to rapid growth of the eventual failure plane. Generation of larger cracks and/or coalescence of minor cracks into larger occurs – leading to macroscopic failure. In that way the average size of the AE sources increases. Larger AE sources tend to generate energetically higher and spectrally lower frequency events. Both the AE maximum bursts amplitude and their frequency spectrum are functions of AE sources mechanisms and of their dimensions.

In general, generation of AE signals with relatively large maximum amplitudes occurs under the following conditions:

– unstable and semi-stable fracture propagation in brittle and quasi-britlle rocks, classification of propagation between these types is determined by the Griffith criterion,
– macrocrack propagation,
– fast propagation of cracks related i.e. to the specific rock structure, high load rate etc.,
– rocks characterized by high degree of anisotropy or with structural defects,
– grain failure (intragranular cracks),
– large preexisting cracks,
– cracks propagating in the direction of the applied force vector.

The generation of AE events with relatively small maximum amplitudes occurs in the following AE sources:

– friction in crack closure stage at grain boundaries and sliding planes,
– twinnings,

– slow and stable propagation of microfractures,
– ductile fractures,
– microfractures in sliding planes and intergranular planes.

The obtained in the present work results indicate that the general qualification of the AE sources on the grounds of maximum burst amplitude values, generated by these sources seems to be rather correct. These results also seem to support the hypothesis of the role of "barriers", particularly these concerning the grain boundaries, in the failure of brittle rocks.

In the first stage of load application i.e. in "crack closure stage" small amplitude AE events were observed but the rates of the events were correlated with the degree of porosity and absorbability of the samples (e.g. sample No 7, Fig. 7).

The samples with large preexisting fractures (e.g. sample No 15, Fig. 6) were characterized by large maximum amplitudes from the beginning of loading.

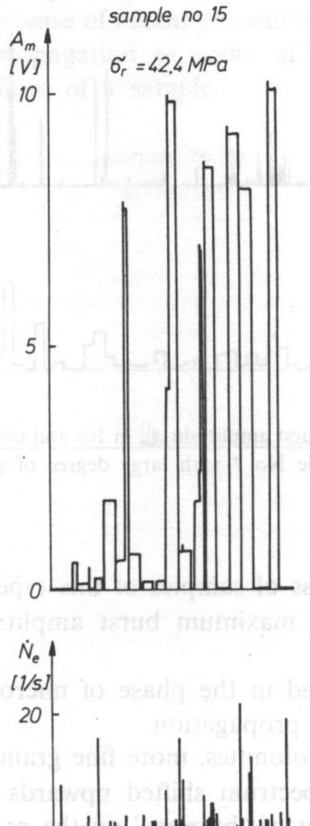

FIG. 6. The plot of AE maximum burst amplitude A_m in 10s and event rate N_e in 1s for dolomite sample No 15 with large preexisting fractures

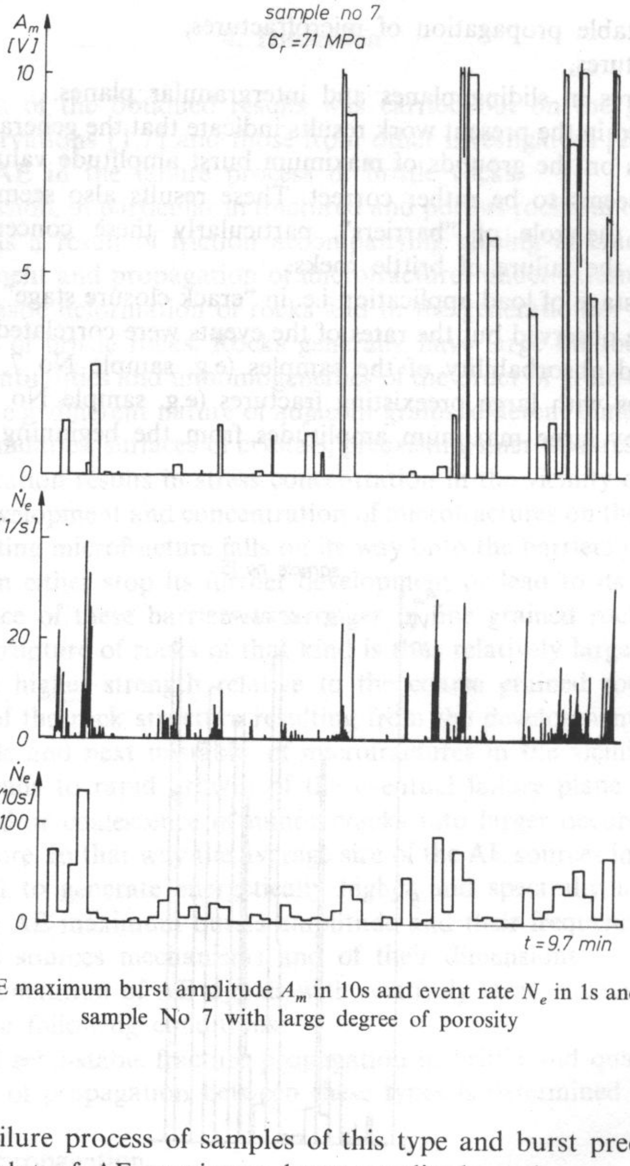

FIG. 7. The plot of AE maximum burst amplitude A_m in 10s and event rate N_e in 1s and 10s for dolomite sample No 7 with large degree of porosity

Monitoring of failure process of samples of this type and burst prediction on the grounds of the plot of AE maximum burst amplitude and event rate is rather difficult.

High amplitudes observed in the phase of microfractures seems to signal the beginning of their unstable propagation.

It has been found that dolomites, more fine grained relative to sandstones, are characterized by the AE spectrum shifted upwards and also by higher strength resulting from stronger effect of "barriers" on the propagation of fractures. It was also found that the role of "barriers" depends on the rate of loading. In case of slow loading rate they have stronger suppressing effect on fracture propagation, which leads to the decrease of average AE source dimensions and eventually to generation of events of higher frequencies and smaller amplitudes e.g. sample No 12 (Fig. 4).

Increase of the loading rate on the other hand, leads to the generation of larger AE amplitude events, e.g. sample No 13 (Fig. 4), as a consequence of higher velocity of microfracture propagation and accompanying increase of the average AE source dimensions.

The present results indicate that brittle rocks can be divided in general into two groups i.e. rocks characterized by explosive failure and non-explosive failure (unstable type and Mogi-type) which is in support of Lord's data [4].

In samples of unstable type the increase of maximum amplitudes and also of event rate is observed only directly prior to their failure. A rather characteristic plot of maximum amplitude and event rate for this type of failure was observed in homogeneous samples of fine-grained sandstone, e.g. sample No 11p (Fig. 7). The prediction of failure in such a case was not possible. However, for the majority of dolomite and sandstone samples examined, as a result of their substantial heterogeneity, a development and stable propagation of microfractures prior to their failure is observed (Mogi-type). An increase of maximum amplitudes indicates the initiation of semi-stable or unstable propagation of some of the microfractures, i.e. the beginning of uncontrolled failure of a sample.

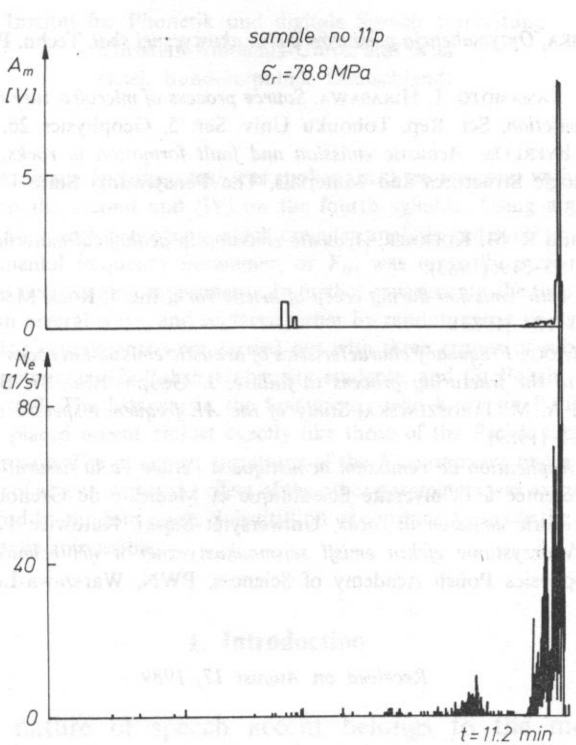

FIG. 8. The plot of AE maximum burst amplitude A_m in 10s and event rate N_e in 1s for sandstone sample No 11p, characterized by explosive failure

Statistical analysis of the results obtained shows that 50% of samples tested had AE maximum amplitude characteristic which was in a high degree similar to their characteristic of event rate. Correlation coefficient between the discussed characteristics was larger than 0.8 for each of these 50% of samples.

However, for 40% of the samples tested the prediction of failure was difficult without information contained in the maximum amplitude plot. Correlation coefficient for this part of samples was smaller than 0.5.

Prediction of failure was practically impossible for the remaining 10% of samples characterized by explosive failure (unstable type) both on the grounds of N_e and A_m.

The performed laboratory experiments seem to support the hypothesis that the AE maximum burst amplitude is not only a parameter which can be measured with the least error introduced by the equipment used or caused by sample dimensions, but firstly it is a parameter which depends significantly on the mechanism of the AE source.

The plot of AE maximum burst amplitude contains information which can be used in predicting impending failure of dolomite and sandstone in situ.

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Received on August 17, 1989