ARCHIVES OF ACOUSTICS
23, 3, 451–456 (1998)

FREQUENCY CHARACTERISTIC OF THE ACOUSTIC EMISSION SIGNAL IN CONCRETE UNDER COMPRESSIVE LOADING

K. POGAN

(30-552 Kraków, 89 Wielicka Str., Poland)

Acoustic Emission measurements are very useful in the investigation of changes taking place in a composite during compressive tests. Among the AE intensity measurements (i.e. counts rate, root mean square, etc.) also the frequency analysis of the AE signal seems to be the useful method. In this paper the analysis of the AE signal characteristic for six different concrete compositions, also for those with silica fumes, is presented. Acoustic Emission signals were measured during quasi-axial compressive tests. The main aim of presented investigations was to demonstrate the spectral patterns of the AE waveforms generated by different concrete structures under compressive loading.

1. Introduction

Acoustic Emission signals are generated in materials as a result of local energy balance instabilities. External actions unsettle the primary state and cause energy radiation in the form of elastic waves called acoustic emission signals (AE). The acoustic emission phenomenon is very complex and depends many of internal and external factors, for instance, among other things: current stress level, load change speed, weighting history and also on the complex material's structure. Elastic waves generated by the source disperse inside or on the surface of the material and deflect are deflected many times. Those waves are received by a special sensor placed on the surface of the tested object. An electronic measurement apparatus makes it possible to observe the whole progress of acoustic emission signals versus time that are very similar in shape to those emitted directly by source. It is therefore vital to analyse the characteristic of these signals and especially their progress over a period of time [7]. The analysis of that progress in destructive tests has been the subject of several works by such authors as: J. Hoła, A. Moczko, J. Mierzwa, K. Pogan and Z. Ranachowski [3, 4, 6, 8, 10]. The obtained results show explicitly the dependence of the parameters of the Acoustic Emission on the concrete structure. It is of essential importance as well for theory as for practical purpose because a quantitative evaluation of the destructive changes appearing at different stress levels can be done using the Acoustic Emission signal parameters. A characteristic recognition of signals generated by the concrete under mechanic actions allows to locate the emission source and, furthermore, to estimate the destruction results, i.e. qualitative description of the progress of the destructive process. The frequency spectrum characteristic of the Acoustic Emission signals would be also a criterion which allows to find the weakest link in the concrete microstructure and structure. BERTHELOT *et al.* [1] apply the frequency analysis of the AE signals related to the fracture mechanism induced during 3-point flexural tests.

This is the origin of research carried on by the author. From the wide investigation program, partly financed by the Polish Scientific Research Committee – Research Project No 7 TO7B 020 08 and referred to the analysis of the frequency characteristic of AE signals in different concrete structures submitted to compressive tests is presented.

Results of the Acoustic Emission signals frequency spectrum analysis in concrete under compressive loading have been presented so far in Poland. In 1996 some papers were published by A. JAROSZEWSKA, J. RANACHOWSKI and F. REJMUND [5] as well as by Z. RANACHOWSKI [9] but they referred to cement pastes and mortars. Those papers were the basis for the following analysis.

2. Experimental

For better a differentiation of the investigated concrete structures, three water-cement ratios (w/c = 0.60; 0.45 and 0.30 respectively) and two types of aggregate were selected, for the series 1, 3 and 5 – crushed aggregate and for the remaining ones (series 2, 4 and 6) – a natural aggregate. Concrete mixes number 3, 4, 5 and 6 were prepared by addition of the superplasticizer FM-6. To strengthen compositions number 5 and 6 micro-filler, silica fumes "Silimic" from Łaziska Ferro-Alloy Works, were added. It should be stressed that silica fume is a by-product of the reduction of high-purity quartz with coal in electric arc furnaces during manufacture of silicon and ferrosilicon alloys. The whole compositions were based on the Portland Cement "Małogoszcz" 45 N. The mix compositions were estimated by the iteration method and are shown in Table 1. Table 2 shows physical properties of the investigated concrete compositions.

Table 1. Concrete mix compositions.

No	W/C coefficient	Ingredents [kg/m^3]					
		Cement	Superplasticizer	Silica fumes	Water	Sand	Gravel
1	0.60	297	–	–	178	676	1248
2	0.60	288	–	–	174	440	1502
3	0.45	333	6	–	147	695	1281
4	0.45	359	7	–	162	433	1480
5	0.30	598	12	60	180	584	1078
6	0.30	645	13	64	194	359	1226

The specimens were 100 mm sided cubes. The hardening lasted for 28 days at the temperature of 18°C and at the relative humidity of 95%.

The hydraulic compressive machine EDU 400 "Fritz Heckert - Leipzig" was used to load the specimens. The surfaces of the specimen were polished to uniform the stress

Table 2. Physical properties of the investigated concrete compositions.

No	W/C coefficient	Compressive strength [MPa]	Density [kg/m^3]	Porosity [%]
1	0.60	24.8	2283	4.8
2	0.60	24.9	2284	5.0
3	0.45	37.0	2323	4.6
4	0.45	34.7	2328	4.6
5	0.30	62.4	2405	4.2
6	0.30	54.2	2400	4.0

distribution and improve the contact with the AE sensor. Additionally, the fibre plates were placed between the specimen and the test machine brackets to minimize the noise generated by the hydraulic drive.

The AE activity was measured by a 1000 kHz AE wideband transducer of WD type connected to a 40 dB/6 µV RMS noise preamplifier and a 43 dB main amplifier. The AE processor registered the AE signals in the "count" mode, i.e. the internal counter registered each excess above the specified rejection level set to 1 V. The AE measurements and the current level of the applied stress were transmitted to a PC compatible computer. Some of the investigated specimens were appropriated for recording the frequency spectrum of signals on two stress levels: between 30 and 60% and between 65 and 95% of the final strength. In this case, the waveform registration procedure was activated when the current Acoustic Emission Activity exceeded 50 counts per second.

A schematic diagram of the measuring set-up and the averaged results of the AE counts sum for the six sets of the examined specimens were shown in the paper [6].

3. Discussion of results

The Acoustic Emission signal analysis showed different time plots for the plain concrete (series 1, 2, 3 and 4) and for that with silica fumes (series 5 and 6) [6]. The concrete with the addition of silica fumes evidenced a σ_{II} critical stress displacement of the range of 70–80% of the compressive strength. For the plain concrete, the typical values of the σ_{I} and σ_{II} stresses are $(0.3 \div 0.4)$ in the range of σ/f_c and $(0.6 \div 0.7)$ in the range of σ/f_c, respectively [3, 4, 6, 8, 10]. This fact causes a smoothing the $\sigma - \varepsilon$ relationship and results from the modification of the cement paste – aggregate contact zone. The major structure damages, arising in σ_{I} to σ_{II} range of the stress level, are located just in this zone. The mentioned zone is compacted by the micro-filler and strengthened by the silica fumes reactivity which transforms the weak portlandite crystals into the strong C-S-H (calcium-silicate-hydrate) phase. The composite structure modifications described above change their physical and mechanical properties by increasing the density and compressive strength in comparison with those of the plain concrete (see Tab. 2), these results in brittleness increasing the high strength concrete.

The neural computation method was applied for the classification of the Acoustic Emission signals. The so called "generalized distance" was chosen as a discernment criterion. The generalized distance between two pattern vectors is the square root of the sum of the squares of all their components subtracted [2, 9].

From the six registered signals' groups, each of nearly 100 samples, the most characteristic and the most frequent frequency spectra were chosen by the computer. Then, for each investigated group an average frequency spectra were found. Within one group, the generalized distances between the particular spectra vary from 2.8 to 4.2, while between each series – from 5.4 to 9.5. This fact indicates that there are significant differences among the frequency spectra for the different concrete compositions. The type of the aggregate among other things influenced these differences. Crushed aggregate, applied in some of the investigated compositions, has a rougher texture which results in a greater adhesion or bond between the particles and the cement matrix. Likewise, the larger surface area of a more angular aggregate provides a greater bond. That is why those concretes have a stronger cement paste - aggregate contact zone. In the frequency spectra for the series with crushed aggregate (1, 3 and 5) a local maximum at the frequency of about 500 kHz can be seen (see Fig. 1).

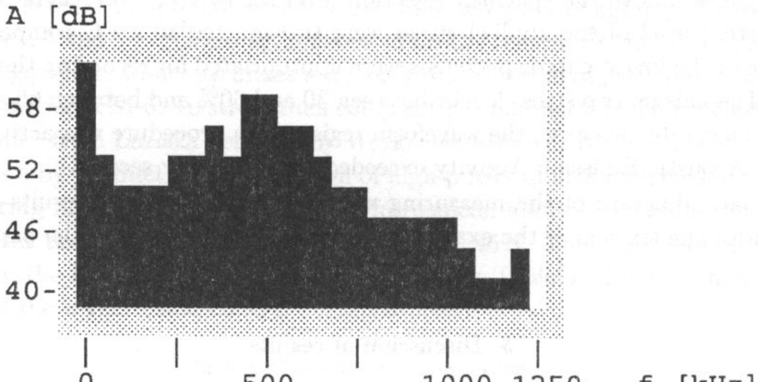

Fig. 1. Frequency spectrum for concrete series with crushed aggregate.

The concrete with silica fumes are also characterized by a strengthened contact zone. For these series the frequency spectra show a smaller participation of the lower frequency signals (see Fig. 2).

During the first loading stage (from 30 to 60% of strength) for the series 1 and 2 sounds characterized by low frequency dominate in frequency spectra. This fact shows that not only defects existing in structure develop but also new microcracks appear in the contact zones between the aggregate particles and the cement paste [5]. These zones are the weakest chains in the structure of compositions 1 and 2 (see Fig. 3). The stronger the composition (remaining series) the better visible becomes the participation of the higher frequency signals. This is connected with cement paste cracking. It can be also seen in the second loading stage (from 65 to 95% of strength) as shown in the Fig. 2.

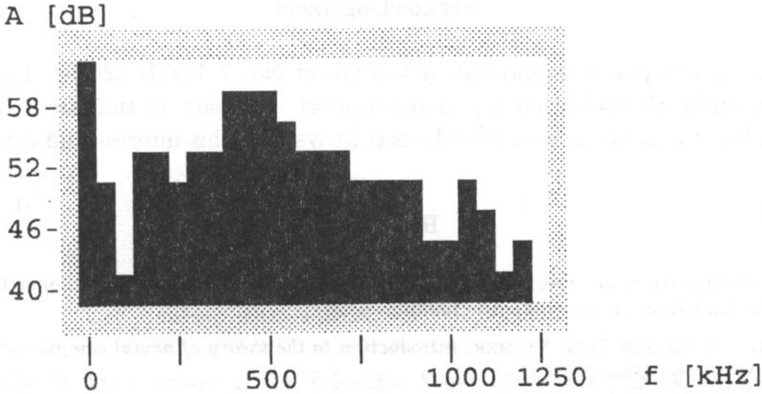

Fig. 2. Less participation of the lower frequency signals for concrete with silica fumes.

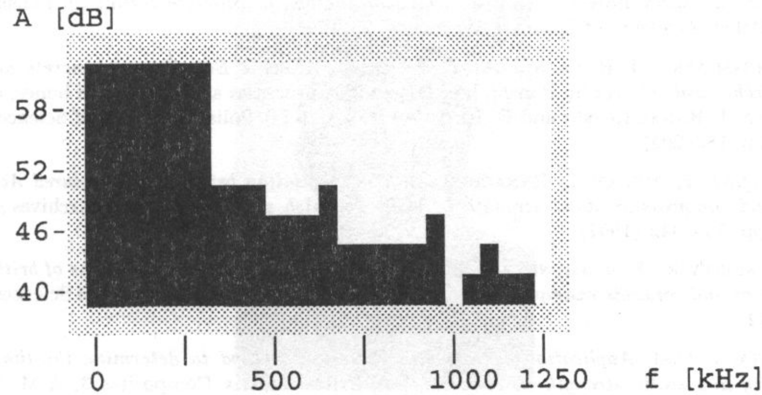

Fig. 3. Frequency spectrum for the weakest compositions.

4. Conclusions

The analysis of the obtained results allows to formulate the following conclusions:

1. The Acoustic Emission measurements made during compressive tests of the concrete compositions appear to be a useful tool providing information on the progress of the destruction processes. The time plots of the Acoustic Emission signal analysis gives only a quantitative image of those processes. The frequency spectra analysis of the Acoustic Emission signals is supplementary to the former one.

2. The frequency spectra analysis of the Acoustic Emission signals with application of the neural computation method gives a qualitative image of the destruction processes occurring during the structure loading. It can help to locate the emission source.

3. The emission source localization can be useful in material engineering, in modifications of existing materials and investigations of new compositions.

Acknowledgement

This paper was partly supported by the Grant No. 7 TO7B 020 08. The author is also very grateful to his Father for moral support necessary in that time. The author also would like to thank Dr Zbigniew RANACHOWSKI for his interest and essential help.

References

[1] J.-M. BERTHELOT *et al.*, *Frequency analysis of Acoustic Emission signals in concrete*, Journal of Acoustic Emission, **11**, 1, pp. 11–18 (1993).

[2] J. HERTZ, A. KROGH, R.G. PALMER, *Introduction to the theory of neural computation* [in Polish], WNT, Warszawa 1995.

[3] J. HOŁA, A. MOCZKO, *Analysis of destructive processes chosen concrete structures with an application of ultrasound and Acoustic Emission methods* [in Polish], PhD Thesis, Institute of Civil Engineering, Wrocław University of Technology, Wrocław 1984.

[4] J. HOŁA, Z. RANACHOWSKI, *Acoustic Emission method in concrete testing* [in Polish], IFTR Reports Polish Academy of Sciences, Warszawa, 26/1991.

[5] A. JAROSZEWSKA, J. RANACHOWSKI, F. REJMUND, *Acoustic Emission in concrete under thermal and mechanical stresses* [in Polish], [in:] Destructive processes and strength of bones, ceramics and concrete, J. RANACHOWSKI and F. REJMUND [Eds.], IFTR Polish Academy of Sciences, Warszawa 1996, pp. 183–208.

[6] J. MIERZWA, K. POGAN, Z. RANACHOWSKI, *The correlation between the fractured Acoustic Emission and compressive static strength in plain and high strength concrete*, Archives of Acoustics, **22**, 3, pp. 333–342 (1997).

[7] J. RANACHOWSKI, F. REJMUND, Z. LIBRANT, *Acoustic Emission investigations of brittle materials. Ceramics and concrete examples* [in Polish], IFTR Reports Polish Academy of Sciences, Warszawa, 28/1992.

[8] Z. RANACHOWSKI, *Application of Acoustic Emission method to determine the limit of proportionality nad static strength in concrete*, [in:] Brittle Matrix Composites 3, A.M. BRANDT and I.H. MARSHALL [Eds.], Elsevier Applied Science Publishers, London and New York, 1991, pp. 234–239.

[9] Z. RANACHOWSKI, *Neural network method in investigations on AE dependence on concrete strength* [in Polish], [in:] Destructive processes and strength of bones, ceramics and concrete, J. RANACHOWSKI and F. REJMUND [Eds.], IFTR Polish Academy of Sciences, Warszawa 1996, pp. 209–220.

[10] Z. RANACHOWSKI, *Measurement methods and analysis of Acoustic Emission* [in Polish], IFTR Reports Polish Academy of Sciences, Warszawa, 1/1997.