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# THE CORRELATION BETWEEN THE FRACTURE INDUCED ACOUSTIC EMISSION AND THE COMPRESSIVE STATIC STRENGTH IN PLAIN AND HIGH STRENGTH CONCRETE

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**In this article Acoustic Emission (AE) measurement results for six different concrete compositions, differing in compressive strength, are presented. The aim of the investigation was to find the dependence between the mechanical strength and the count sum of the registered Acoustic Emission. AE signals were measured by a quasi-axial compression test. Two acoustical parameters were examined and compared with the compressive strength and static strength of the compositions tested. The first one was the AE activity during the complete compression process and the second one was the AE activity measured to the point of the start of the instable crack growth propagation process.**

## 1. Introduction

The load increase applied to a concrete structure causes a stress-vave generation process, reflecting the damages occuring in the structure. The Acoustic Emission measurements made in concrete elements under mechanical and thermal stress were described in [1–8]. The mentioned authors confirm the dependence between the parameters of the measuerd AE signal and the damage process in the loaded structure. This may lead to improvements of the concrete composition optimalisation, may help to recognize the destructed microstructures and to determine the mechanical strength of the investigated compositions.

The Acoustic Emission sensor attached to the tested structure converts the energy of the elastic waves mentioned above into electrical signals. The state-of-art in the AE instrumentation allows to detect very small signals, the power of which is of the order of several picowatts. The sensivity of the AE processors allows them therefore to monitor the destruction processes within a wide range of load levels. This makes it possible to distinguish three separate regions with different AE records on the plot of the AE activity expressed as a function of the applied load:

a) Initial loading noise – the region is characterized by relatively high level of AE activity caused by the initial compaction of the concrete matrix and by the damages on the contact surface between a loading machine and a specimen.The effect described here is hardly detectable in high – strength concretes.

b) Region of the constant AE activity – with a lower level of AE activity caused by the stable growth of the internal microcracks.

c) Precursor to failure – the region of very rapidly increasing AE activity caused by the unstable growth of the microcracks leading to the failure of the structure.

The limit of the first one of the discussed regions corresponds to the limit of proportionality (LOP) that is to be determined from the stress-strain curve plotted during the compression test. This characteristic stress level is also called the initiation stress $\sigma_{\mathrm{I}}$ [1, 6, 7]. The limit of the second region has the notation $\sigma_{\mathrm{II}}$ and corresponds to the static strength [1, 2]. The determination of $\sigma_{\mathrm{II}}$ with the use of the AE measurement is not a complex task since at this stress level there is a significant increase of AE activity. The determination of $\sigma_{\mathrm{I}}$ is more difficult, however. The changes of AE activity preceding and following this stress level are less distinct and require a careful signal processing.

By now, however, there is no satisfactory quantitative relationship between the AE activity and the strength of tested compositions. This relationship, especially derived for high strength concretes, will be discussed in the following paper.

## 2. Experimental materials and methods

Six concrete compositions, labelled 1 to 6 and differing in their compressive strength were prepared as indicated in Table 1. Each of the prepared series of specimen consisted of 10 members. The compressive strength for these compositions was estimated in the range of 28 – 64 MPa. The cement of Grade "45" was used. The compositions labelled 1, 3 and 5 were based on crushed aggregates and the remaining compositions were based on river aggregates. Additionally, to make high strength compositions, a plasticizer was added to the compositions labelled 3, 4, 5, 6 and silica fume was added to the compositions labelled 5, 6. The specimens were 100 mm sided cubes. The hardening lasted for 28 days at the temperature 18° C and rel. air humidity 95%.

The compression tests were done using the instrumentation shown in Fig. 1. The hydraulical compression machine of type ZT 60 was used to load the specimen. The surfaces of the specimen were polished to uniform the stress 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 noises generated by the hydraulic drive.The loading was made with $5\,\mathrm{N/cm^2 \cdot s}$ of force increase as it is recommended in [6].

**Table 1.** Mix proportions of concretes used for the investigation.

| Composition No. | Water to cement ratio | Components [kg/m$^3$] | | | | | | Plasticity measured by slump test method [cm] |
|---|---|---|---|---|---|---|---|---|
| | | Cement | Plasticizer | Silica fume | Water | Sand | Aggregates | |
| 1 | 0.60 | 297 | – | – | 178 | 676 | 1248 | 6 |
| 2 | 0.60 | 349 | – | – | 210 | 532 | 1818 | 7 |
| 3 | 0.45 | 284 | 6 | – | 147 | 695 | 1281 | 7 |
| 4 | 0.45 | 359 | 7 | – | 162 | 433 | 1480 | 6 |
| 5 | 0.30 | 598 | 12 | 60 | 180 | 584 | 1078 | 1 |
| 6 | 0.30 | 645 | 13 | 64 | 194 | 359 | 1226 | 1 |

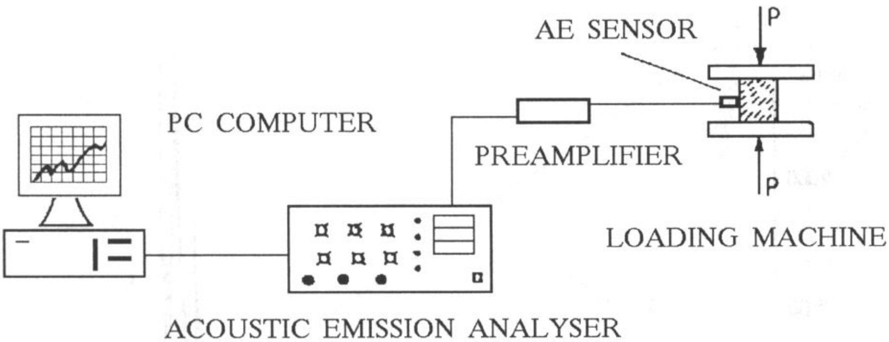


Fig. 1. The instrumentation used during the investigation.

The AE activity was measured by the 200 kHz AE resonance transducer connected to the 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 beyond the specified rejection level set to 1 V. The AE measurements and the current level of applied stress were transmitted to the PC compatible computer. The averaged results of the AE counts sum and the related compressive strength of the six sets of the examined specimen are shown in Table 2.

**Table 2.** Averaged AE counts sum measured for the investigated concretes.

| Composition No. | Compressive strength [MPa] | AE counts sum registered: | |
|---|---|---|---|
| | | until the end of the stable crack propagation region [pulses] | during the entire compression test [pulses] |
| 1 | 25.9 | 128726 | 277073 |
| 2 | 24.4 | 156273 | 216203 |
| 3 | 34.8 | 84189 | 139024 |
| 4 | 35.9 | 91918 | 176468 |
| 5 | 63.6 | 516097 | 886318 |
| 6 | 52.1 | 254242 | 471905 |

## 3. Discussion of the results

The characteristic time plots of the registered AE counts rate during loading the specimens of type 1 and 5 are shown in Figs. 2 and 3, respectively. The AE activity shown in Fig. 2 is typical of the plain concrete. The linear stress increase and the related crack growth process makes the exponential AE counts rate increase. The exponential AE counts rate increase may be explained by the assumption that the number of the AE sources is proportional to the permanently increasing size of the cracks. The example of the AE activity registered in the high strength concrete present the different trend. After the initial counts rate increase a local region of quasi-stable AE generation is observed (as shown in Fig. 3). The crack growth in the mentioned quasi-stable region is blocked on the improved microstructure of the high strength concrete specimen.

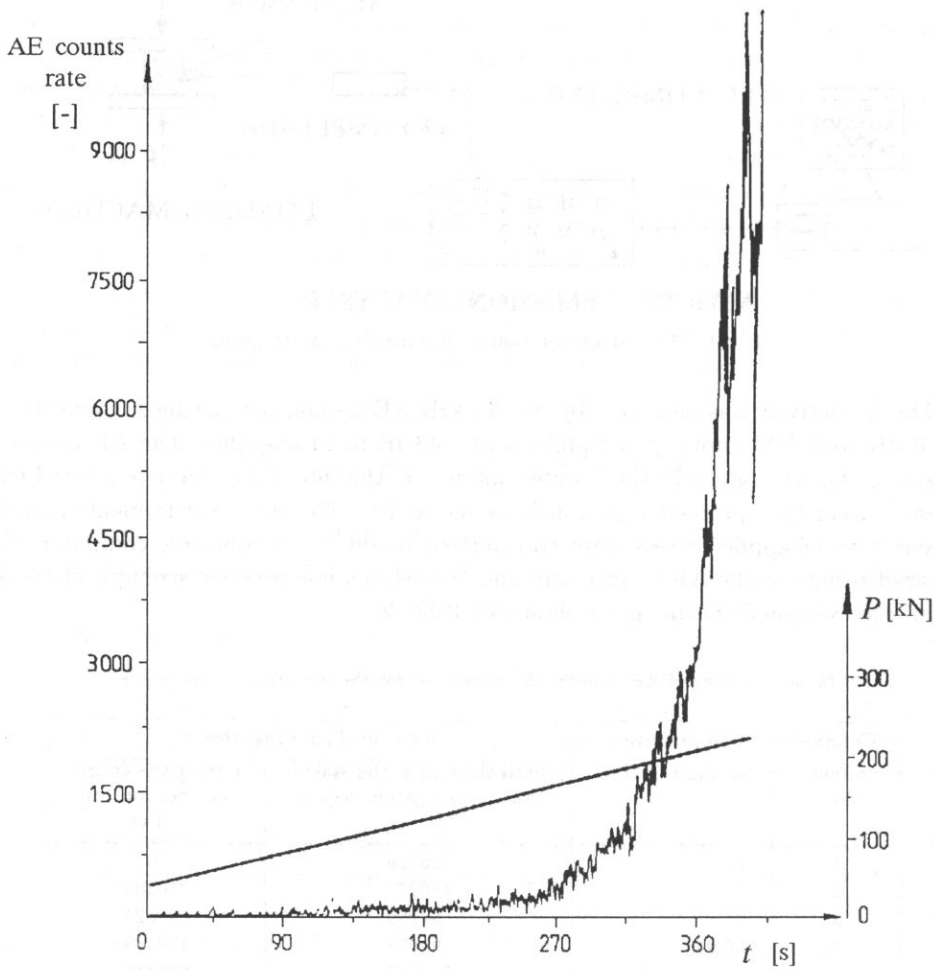


Fig. 2. Example of Acoustic Emission activity vs time plot, registered in compressed concrete composition No. 1.

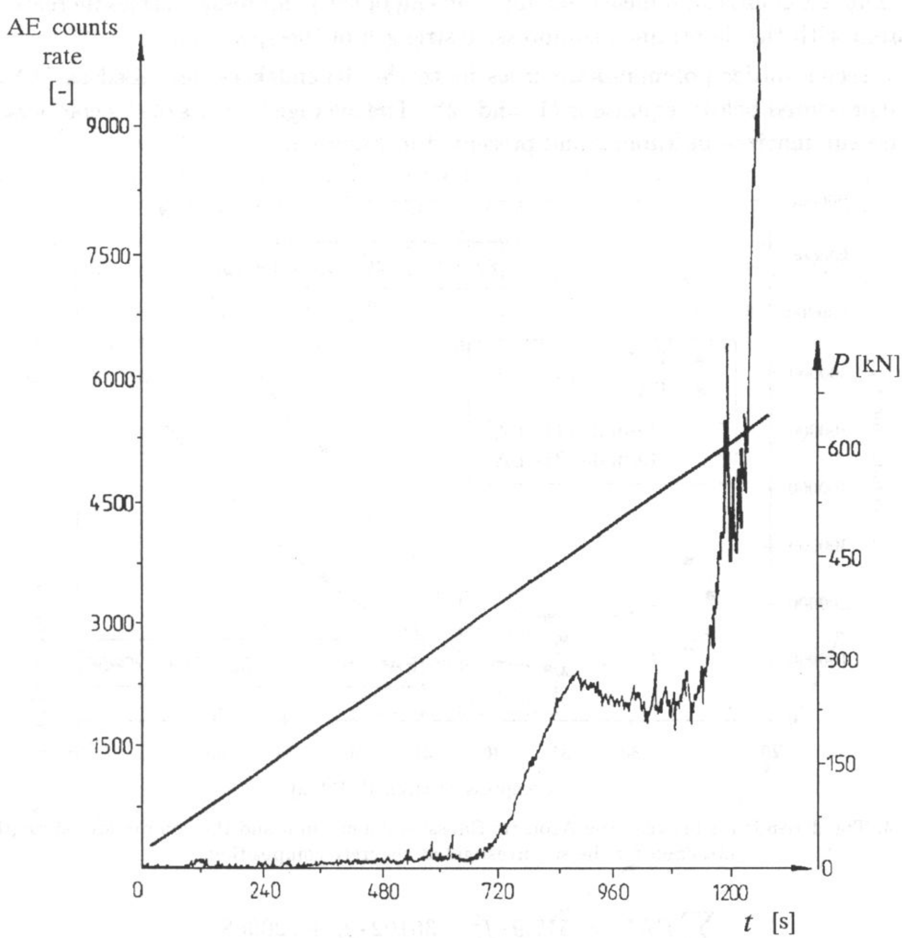


Fig. 3. Example of Acoustic Emission activity vs time plot, registered in compressed concrete composition No. 5.

The averaged records of the AE activity registered during the compression tests were used to determine the dependence upon the mentioned acoustical parameter and the averaged compressive strength which was evaluated for each concrete.

Two concurrent strategies were applied to determine the dependence mentioned above:

A. The AE counts sum measured until the end of the stable crack propagation region was compared with the determined compressive strength of the specimen. The recognition of the end of the stable crack propagation region, when the current couns rate exceeded the threshold value was performed by a software prepared to process the experimental data. The idea of the presented strategy of data processing led to the determination of the specimen parameters without the need of a final destruction of the tested structure.

B. The AE counts sum measured until the end of the compression stress increase was compared with the determined compressive strength of the specimen.

The second-order polynominal curves fit to the dependences described as (A) and (B) are presented below (equations (1) and (2)). The averaged results of the comperssion tests are summarized in Table 2 and presented in Figure 4.

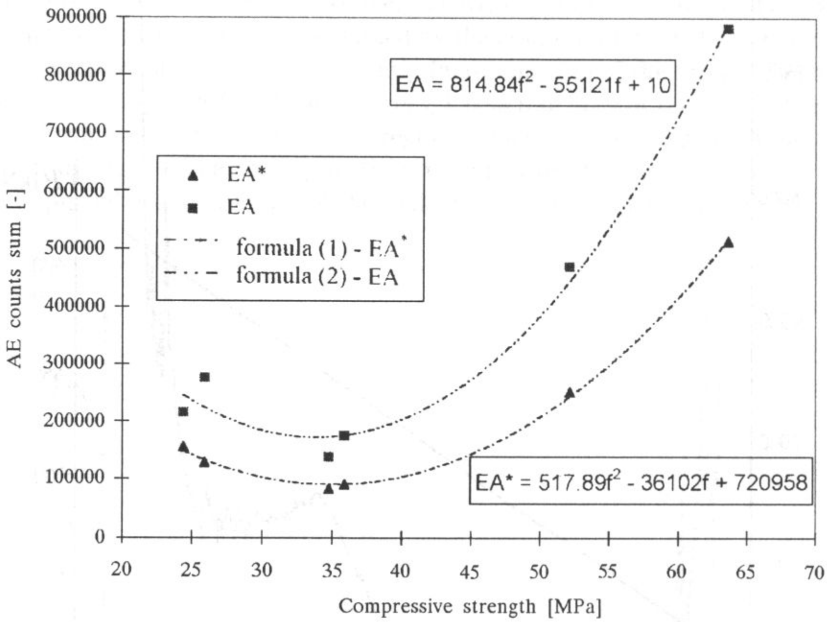


Fig. 4. The dependence between the Acoustic Emission counts sum and the compressive strength obtained for the six investigated concrete compositions.

$$\sum \mathrm{EA}^* = 517.9 \cdot f_c^2 - 36102 \cdot f_c + 720958, \quad (1)$$

$$\sum \mathrm{EA} = 814.8 \cdot f_c^2 - 55121 \cdot f_c + 10^6. \quad (2)$$

where $\sum \mathrm{EA}^*$ – AE counts sum registered until the end of the stable crack propagation region, $\sum \mathrm{EA}$ – AE counts sum registered during the entire compression test, $f_c$ – compressive strength, [MPa].

The correlation coefficients related to the experimental results, presented in Table 2 and by the Eqs. (1) and (2) are equal 0.99 and 0.98, respectively. This confirms the usefullness of the testing strategy labelled A and discussed above. According to that strategy there is a possibility to cease the loading of the concrete elements when the first signs of the unstable crack propagation occurs. Some authors [3, 4] suggest the possibility of e self-curing of the fresh concrete after such a test. Using the experimental results listed in Table 2, it is also possible to derive an another regression curve presenting the dependence between the compression strength, $\sum \mathrm{EA}^*$ and $\sum \mathrm{EA}$.

$$(3) \qquad \frac{\sum \mathrm{EA}^*}{\sum \mathrm{EA}} = 0.645 \cdot f_c\,.$$

The coefficient of proportionality (0.645) in Eq. (3) denotes the averaged stress level corresponding to the end of the stable crack propagation level for the tested compositions. In some papers [1, 3, 5, 6, 7] the end of stable propagation level in taken as approx. equal to the static strength $\sigma_{\text{II}}$ of the tested structure. The analysis of the AE activity may be also used to determine the start of the stable crack propagation region $\sigma_{\text{I}}$. This characteristic material strength parameter is estimated as approx. equal to the LOP. The stress level $\sigma_{\text{II}}$ is determined as the start of the final rapid noise increase region, respectively. The two characteristic stress levels, $\sigma_{\text{I}}$ and $\sigma_{\text{II}}$ can be recognized in the Fig. 5. and Fig. 6 constructed for all the six concrete compositions. The horizontal axis of the mentioned figures corresponds to the normalized stress understood as a fraction of the ultimate stress. The AE counts increase registered for the consecutive 10% of the normalized stress increase, is shown on the vertical axis.

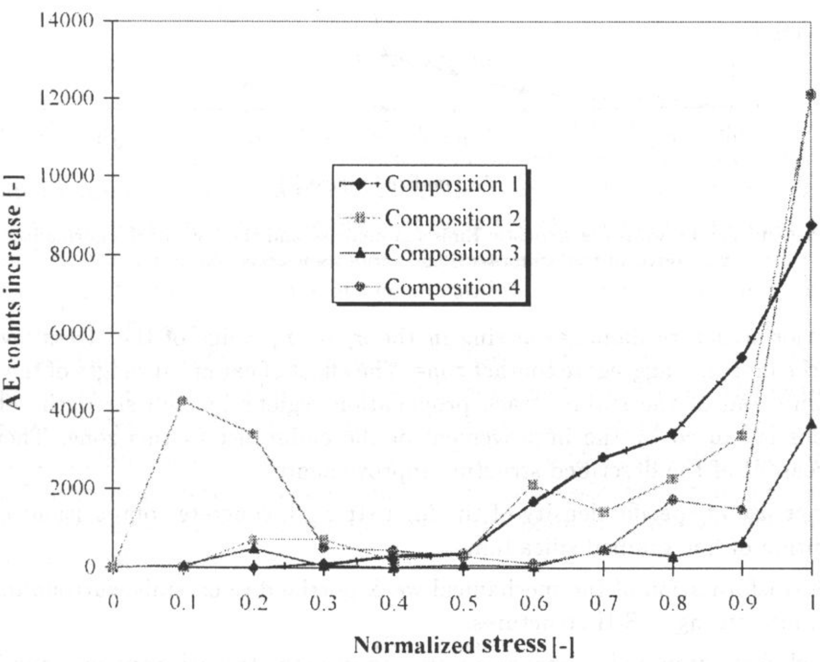


Fig. 5. The dependence between the Acoustic Emission increase and the level of the normalized strain registered in the compressed concrete compositions No. 1 – 4.

The determination of $\sigma_{\text{I}}$ and $\sigma_{\text{II}}$ with the use of Fig. 5 leads to the conclusion that for all plain concrete compositions the characteristic stress levels are nearly equal. The $\sigma_{\text{I}}$ level corresponds to the $(0.3 \div 0.4)$ range of $\sigma/f_c$ and the $\sigma_{\text{II}}$ lone to the $(0.6 \div 0.7)$ range of $\sigma/f_c$. The characteristic stress levels presented for the high strength conctretes in Fig. 6 are radically different. There is an absence of the changes of the AE activity related to the $\sigma_{\text{I}}$ level and the $\sigma_{\text{II}}$ level is greather than 0.7 $\sigma/f_c$. The reason for the presented differences in the mechanical properties of plain and high strength concrete may be explained on the basis of microstructural investigations [3].

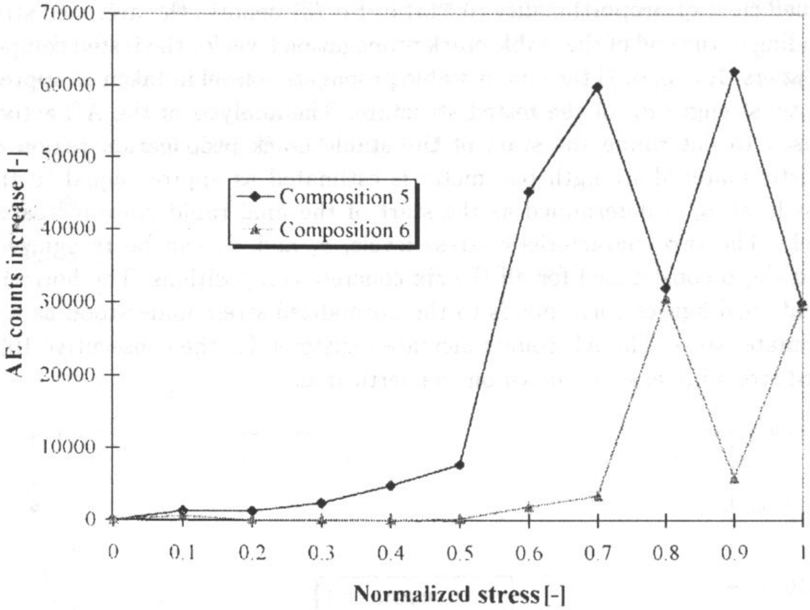


Fig. 6. The dependence between the Acoustic Emission increase and the level of the normalized strain registered in the compressed concrete compositions No. 5, 6.

The major structure damages arising in the $\sigma_{\text{I}}$ to $\sigma_{\text{II}}$ range of the stress level are located in the mortar – aggregate contact zone. The effect of extended ranges of the linear strength limit and of the stabile crack propagation regions in high strength concrete compositions is caused by the improvement of the endurance of this zone. There are following reasons of the described structure improvements:

- the increase of specific density of the high strength concrete compositions caused by the addition of fine grained silica fume,

- phase trasformation of the mechanical weak portlandite crystals, surrounding the aggregates, into strong C-S-H structures.

The crack formation and propagation process in high strength concrete may be reconstructed with the use of the AE activity record shown in Fig. 6. in addition of the data presented in the Table 2. However the compressive strength of the high strength concretes is $2 \div 5$ times higher than that of the plain concrete, but the region of unstable crack propagation is relatively short in the high strength concretes. This results in increased brittleness of high strength concretes.

The influence of the kind of the aggregates used in the concrete compositions was discussed in [1], where the plain concrete compositions were prepared by using basalt, limestone and river aggregates. The results of measurements of the characteristic stresses $\sigma_{\text{I}}$ and $\sigma_{\text{II}}$ during these tests are shown in Table 3. The important conclusion is that the chemically active limestone aggregates form a durable contact zone in connection to the mortar despite its worst mechanical strength among the aggregates investigated.

**Table 3.** The dependence of characteristic stress levels $\sigma_{\mathrm{I}}$ and $\sigma_{\mathrm{II}}$ on aggregate type [1].

| No. | Aggregate type used in concrete | Average stress levels | |
|---|---|---|---|
| | | $\sigma_{\mathrm{I}}$ | $\sigma_{\mathrm{II}}$ |
| 1 | basalt | $0.45f_c$ | $0.80f_c$ |
| 2 | limestone | $0.51f_c$ | $0.88f_c$ |
| 3 | river aggregate | $0.44f_c$ | $0.78f_c$ |

A similar mechanism seems to exist in the high strength concretes investigated by the authors of this paper. The major reason of increased durability of the investigated high strength concretes is the reduced number of structure deffects in the contact zone due to the additional fine grain components.

## 4. Conclusions

The Acoustic Emission measurements made during the compression tests of the concretes are a useful tool to provide information on the destruction processes in the investigated material. The changes of the AE activity, related to the crack growth and formation processes, enable the determination of the characteristic stages of destruction described by the $\sigma_{\mathrm{I}}$ and $\sigma_{\mathrm{II}}$ parameters. The parameters specified above are especially important for the understanding of the durability of different concrete compositions under long – term quasi-static loads.

The presented results of the Acoustic Emission measurements show the different destruction schemes in the plain and in the high strength concretes. The latter material is characterized by a relative small intensity of the crack formation process in the region of the initial and intermediate load and by a rapid progress of the instable crack propagation region. The acoustic method to determine the characteristic stress $\sigma_{\mathrm{I}}$ in the high strength concrete, similar to the procedure applied to the plain concrete will be the object of further investigations.

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