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Analysis of destructive processes in unloaded early-age concrete with the acoustic emission method

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Abstract

The study presents the analysis of destructive processes that occur in early-age concrete with the use of the IADP method of acoustic emission signal analysis. The tests were conducted for concrete specimens made with basalt aggregate, which was cured at a constant temperature of 22° C, but were different with respect to cement class, admixtures used and the curing methods. Three classes of AE signals were identified. The signals were generated by destructive processes related mainly to concrete shrinkage due to water evaporation and described as: microcracks at the aggregate – cement paste interface, microcracks in the cement paste, and the formation of microcracks on concrete surface. It was shown that the IADP method could be used to identify and evaluate the destructive processes that develop in early-age concrete.

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Keywords: early-age concrete; destructive processes; the acoustic emission method

1. Introduction

Internal stresses develop in unloaded concrete during the processes of its setting, hardening and drying, what was described by Godycki-Ćwirko [1] and Neville [2]. At the sites of stress concentration, where stresses exceed concrete tensile strength, microcracks are formed at the aggregate – cement paste interface and in the paste itself as it was reported by Kurdowski [3] and Flaga [4]. Due to the action of destructive factors, those microcracks may

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propagate outwards until they reach the element surface, thus lowering the tightness of the shell concrete and reducing concrete protective function, and in some cases, causing even a failure of, e.g., tanks, what was indicated by Godycki-Ćwirko et al. [5]. It is therefore important to seek methods for investigating destructive processes in early-age concrete (unloaded concrete) to assess the quality of concrete workmanship. Especially given the fact that the methods applied, based primarily on microscopic observations conducted e.g. by Brandt and Jóźwiak-Niedźwiecka [6], allow us to observe destructive processes (microcracks), but due to technical reasons, they do not ensure tracking the defects or analysing the whole of the element of concern.

On the basis of the preliminary tests, it was stated that the acoustic emission method named IADP (Identification of Active Destructive Processes) could be employed to identify and assess the destructive processes that occur in early-age concrete.

The acoustic emission (AE) method has already been applied to analyse the destructive processes taking place in concrete. The method, however, was used in many studies conducted by Rucka and Wilde [7], Hoła [8], Świt [9], Gołaski et al. [10], Goszczyńska [11] for loaded concrete, for which acoustic emission signals that primarily accompany the initiation and growth of microcracks observed on the element surface were recorded and analysed. The initial results of the analysis of destructive processes in unloaded early-age concrete, namely microcracks in the cement paste and at grain boundaries, carried out using the IADP method were presented in studies described by Goszczyńska et al. [12] and Bacharz [13].

To be able to practically apply the IADP acoustic emission method as a diagnostic tool for concrete structures, it is necessary to perform analyses related to the validation of identification of destructive processes that occur in concretes independently of their different composition, curing regime, temperature conditions and humidity.

The study presents the tests performed on concrete specimens, made with basalt aggregate, with the acoustic emission method. In the tests, concrete specimens made of concrete strength class (C30/37, C40/50), cement grade (CEM I, CEM III) and subjected to various curing regime were examined. The analysis of the identification of destructive processes was based on experimental results obtained from three series in which nine concrete specimens were examined (3 series x 3 items).

The test results confirmed that the IADP acoustic emission method could be applied to identify and monitor destructive processes in early-age (unloaded) concrete, thus it can become a useful tool for the evaluation of concrete structures at their early age.

2. The IADP acoustic emission method

The IADP acoustic emission method is a modification of the RPD (Recognition of Destructive Processes) method which was developed by Świt [9] as a diagnostic tool for prestressed concrete elements, especially bridges under service load. Gołaski et al. [10] and Goszczyńska [11] present a modification of the method, named IADP – Identification of Active Destructive Processes, and its application to detection, assessment and location of destructive processes that accompany the action of load in non-prestressed reinforced concrete elements. The use of the IADP method for the analysis of destructive processes in early-age concrete is discussed by Goszczyńska et al. [12] and Bacharz [13].

Main idea of the IADP method is that the defect which occurs in the concrete specimen (Fig.1a) emits elastic waves, which are received by acoustic sensors and converted into electric signals. Then, the signals are amplified by pre-amplifiers and recorded, by the processor. Subsequently, recorded signals are grouped and compared with the database of reference signals of destructive processes (established on the basis of 12 parameters of the AE signal - counts, counts to the peak amplitude, signal duration, signal rise time, signal amplitude, signal energy, signal strength, average effective voltage, absolute energy, average signal frequency, reverberation frequency and initiation frequency) compiled beforehand under laboratory conditions. Finally, the recorded signals are assigned to respective signal classes as it was reported by Świt [9].

The preliminary reference signal database founded by Goszczyńska et al. [12] comprises four signal classes corresponding to destructive processes which may be the source of the acoustic wave in the early-age concrete.

The destructive processes assigned to individual signal classes are as follows:
Class 1 – Microcracks in the cement paste,
Class 2 – Microcracks at the aggregate-paste interface,
Class 3 – Formation of microcracks on concrete surface,
Class 4 – Growth of microcracks.

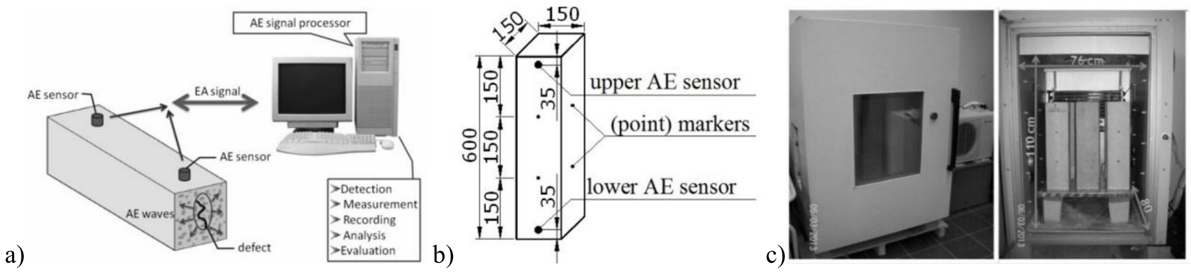

Fig. 1. a) Diagram of the IADP method for unloaded concrete, b) Test specimen with measurement sensors installed, c) Test stand. [13].

3. Testing schedule

The tests were performed on 9 concrete specimens (3 series labelled B-2, B-3 and B-5, each containing 3 specimens), having the following dimensions: 150x150x600 mm, made with basalt aggregate and two cement grades, with and without admixtures, which were subjected to two curing regimes. The information on specimens and curing regimes is given in Table 1.

Table 1. Notation for specimen series, description of basalt aggregate concretes, curing regimes and measurement conditions.

Series	Cement	Admixtures	w/c	Curing conditions	Temperature	Concrete strength class
B-2	CEM I 42.5 N - MSR/NA	Superplasticizer - based on modified polycarboxylates Air Entraining Admixture – an aqueous solution of a complex mixture of organic acid salts	**0.4**	10 days water curing	**22°±2°C** laboratory conditions	**C40/50**
B-3	CEM I 42.5 N - MSR/NA	absent	**0.5**	10 days water curing	**22°±2°C** thermal chamber	**C40/50**
B-5	CEM III/A 42.5 N -LH/HSR/NA	absent	**0.5**	no curing	**22°±2°C** thermal chamber	**C30/37**

After demoulding, B-2 series specimens (3 items) and B-3 series specimens (3 items) were placed in water for 10 days to avoid autogenous shrinkage, and then the tests were run – for B2 specimens under laboratory conditions, for B3 specimens in thermal chamber. Tests on B-5 series specimens (3 items) were performed directly after demoulding in thermal chamber.

Metal (point) markers were fixed on to four walls of each specimen to measure strain. Two AE sensors were installed on one wall of each specimen, at a distance of 35 mm from the upper and lower specimen edges, as shown in Fig. 1b.

The specimens, prepared as described above, were placed in a thermal chamber specially configured for the tests (B3 and B5 specimens) or in laboratory (B3 specimens). The chamber in details was described by Bacharz [13]. The stand, presented in Fig. 1c, was set up in such a way as to ensure the pre-set temperature conditions throughout the tests, and also to eliminate external noise impact. The humidity in the chamber and in laboratory was not controlled but measured. Humidity change during 28 days is presented in Fig. 2.

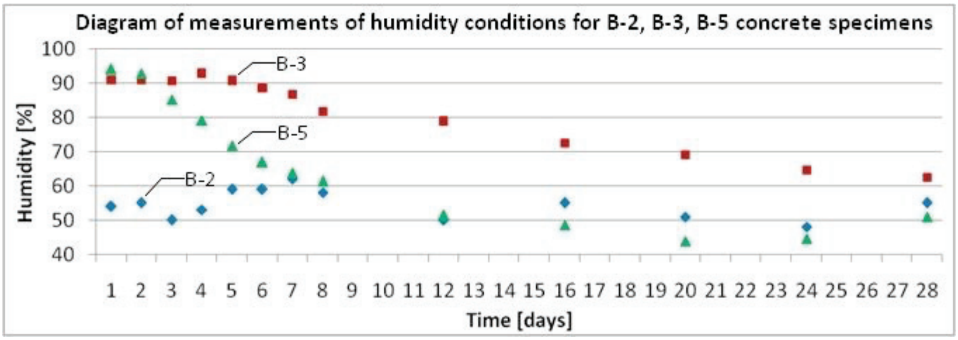

Fig. 2. Diagram of measurements of humidity conditions over test time for B-2, B-3 and B-5 concrete specimens.

The tests were conducted for 57 days at stabilised temperature of 22±2^{0}C. In the tests, run in 12-hour cycles, AE signals were measured and signal classes corresponding to destructive processes, obtained with the comparative analysis, were recorded. To measure the acoustic waves resonant sensors with flat characteristics in 30-80 kHz frequency range (selection of sensor array was described by Goszczyńska et al.) and 40 dB pre-amplifiers were used. The MISTRAS software was employed to record acoustic signal sand to detect their location. The Noesis 4.0 software made it possible to carry out a comparative analysis of recorded signals, to evaluate those signals and categorize them in accordance with the reference signal database.

In the tests, strain was measured using contact-type extensometer with 8 inch base and specimens were weighed to determine water mass loss. At first, measurements were taken every day, afterwards, every second and every tenth day.

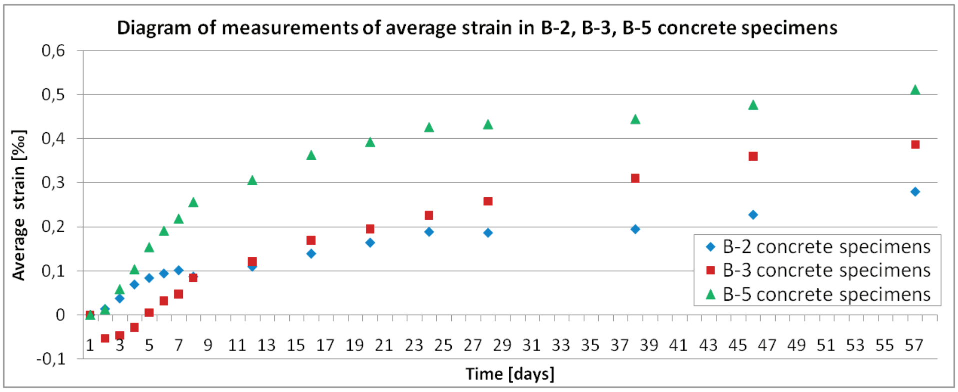

Fig. 3. Diagram of measurements of average strain over test time in B-2, B-3 and B-5 concrete specimens.

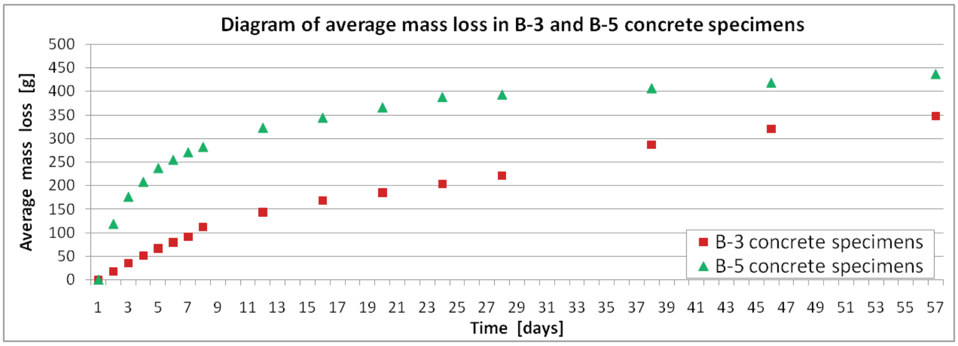

Fig. 4. Diagram of average mass loss over test time in B-3 and B-5concrete specimens.

On the basis of the analysis of the average data in the diagram showing average strain of three samples it can be stated that concrete modified with admixtures (B-2) was characterised by the least strain increment in time (Fig. 3). After 57 days, average strain in this concrete was 0.28‰. For the same testing period a greater strain increment was found in B-3 concrete specimens i.e. without admixtures) namely 0.39‰. The highest increment of shrinkage strain was observed in specimens made from B-5concrete, which was neither modified with admixtures nor cured. After 57 days mean strain in B-5 concrete was 0.51‰.

As the drying period increased, B-2 and B-3 concrete specimens showed mass loss, which depended on the curing regime (Fig. 4). After 57 days of testing, mass loss in B-3 concrete specimen was 312 g, whereas in B-5 concrete specimen this value was 436 g. It can be concluded that the results obtained in the tests were consistent with the theoretically-forecast performance of the concretes of concern.

4. Results of AE signal measurements

Acoustic emission tests were conducted for 57 days under stabilised temperature conditions in the chamber or in laboratory, i.e. at 22±2^{0}C. AE signals measurement was performed for 12 hours period in following days as it is shown in Figs 5, 6, 7. Relying on previously compiled reference signal database, AE signals were analysed and classes corresponding to destructive processes were identified. In the tests, Classes 1, 2 and 3 were recognised.

4.1. Number of AE signals

Figs 5, 6, 7 show, in an exemplary manner, a number of AE signals as a function of time, recorded by the lower sensor on one specimen of each series: B-2, B-3 and B-5. As it is mentioned above, number of signals was counted for 12 hours period of measurement.

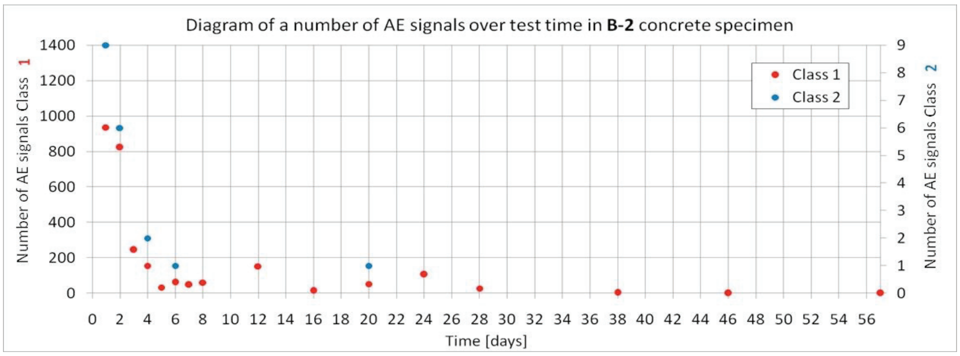

Fig. 5. Diagrams of a number of AE signals over test time in B-2, B-3 and B-5 concrete specimens.

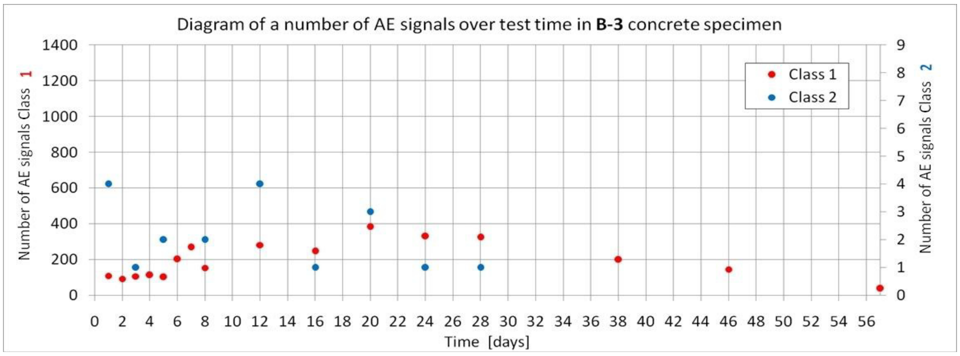

Fig. 6. Diagrams of a number of AE signals over test time in B-2, B-3 and B-5 concrete specimens.

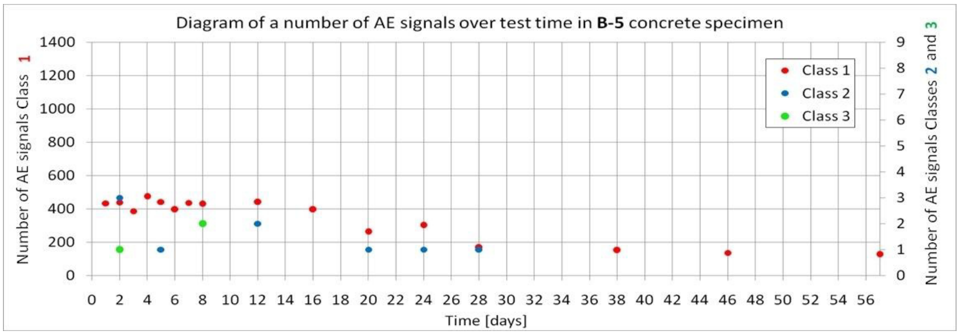

Fig. 7. Diagrams of a number of AE signals over test time in B-2, B-3 and B-5 concrete specimens.

In all specimens (B-2, B-3 and B-5), Class 1 and 2 signals were recorded. Class 1 signals were detected throughout the whole measurement period (57 days), first in large numbers and afterwards the number of signals was greatly reduced. Class 2 signals, which occur in a far smaller number than Class 1 signals, generally vanish after 28 days.

In all B-5 concrete specimens, Class 3 signals were detected. Visible microcracks were also found on the lateral surfaces of the specimens. Surface microcracks were not detected on B-2 and B-3 concrete specimens; neither was Class 3 signals recorded for them.

This observation confirms that Class 3 signals accompany microcrack formation on the concrete surface. It is consistent with the results obtained previously by Bacharz [13] for specimens made with the same cement and with limestone aggregate, which were subjected to 10-day water curing and cyclic temperature changes.

Class 4 signals, corresponding to microcrack growth, were not recorded in any B-5 concrete specimen, which is confirmed by the lack of microcrack growth on their surfaces.

4.2 Energy of AE signals

Figs 8 and 9 show unit energy (energy/number of signals) of Class 1 and 2 AE signals, which was computed for each concrete series (B-2, B-3 and B-5) on the basis of the data from all sensors mounted on the specimens of a given series, recorded over 12 hours periods. Fig. 10 presents unit energy of Class 3 AE signals, which were recorded only for series B-5 specimens.

Mean unit energy values are also presented in this figures (broken lines). It was computed as the energy sum from all signals of given Class (collected for each concrete series within 28 days) divided by number of signals. Energy is one of 12 parameters under which the reference data base for destructive processes is created. Number of signals recorded during 28 days is also presented in Figs 8, 9 and 10.

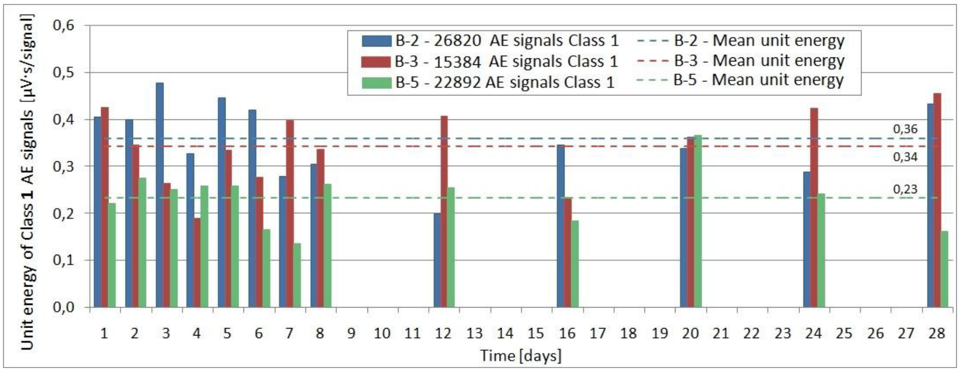

Fig. 8. Unit energy of Class1 AE signals for B-2, B-3 and B-5 concrete specimens.

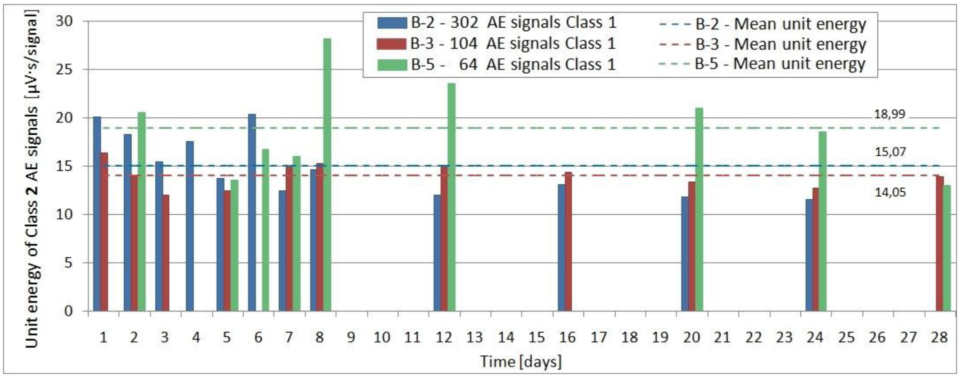

Fig. 9. Unit energy of Class 2 AE signals for B-2, B-3 and B-5 concrete specimens.

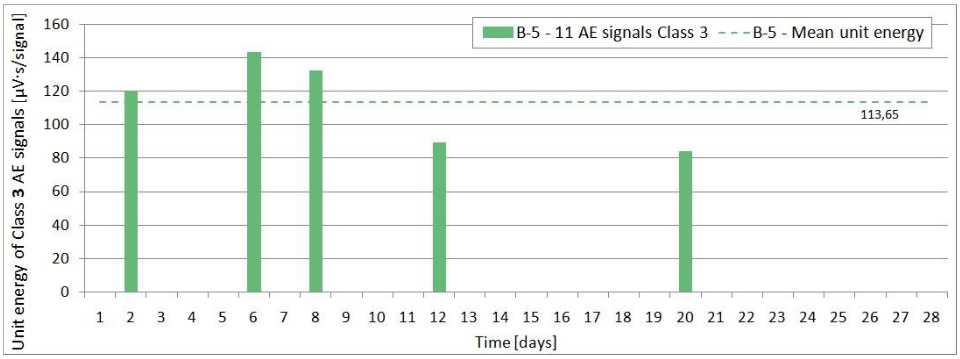

Fig. 10. Unit energy of Class 3 AE signals for B-5 concrete specimens.

The results obtained in the tests, for which variation in the unit energy values can be categorised as low/ moderate (classic coefficient of variation V≤ 20% - low; 20≤ V≤ 50% - moderate), were summarized in Table 2.

Table 2. Selected statistical parameters determined for B-2, B-3 and B-5concrete specimens.

	energy/number of signals (mean values for 28 days)						
	Concrete B-2 (with admixtures)		Concrete B-3 (without admixtures)		Concrete B-5 (without admixtures)		
	Class 1	**Class 2**	**Class 1**	**Class 2**	**Class 1**	**Class 2**	**Class 3**
Mean unit energy [μV·s]	0.36	15.07	0.34	14.05	0.23	18.99	113.65
standard deviation	0.08	3.22	0.08	1.32	0.06	4.89	26.15
coefficient of variation V [%]	**22.3**	**21.4**	**23.53**	**9.43**	**25.9**	**25.7**	**23.01**

For B-3 concrete (without admixtures) the observed coefficients of variation of unit energy of Class 2 signals is at the level of 9%, which indicates low variation in results. The other results showed moderate variation, which ranged 21- 26%. For all specimens of different specimen series, unit energy of Class 1 AE signals (Fig. 8) shows similar values and ranges 0.36-0.23 [μV·s], for B-5 specimens, however, it is slightly lower. The value of unit energy of Class 2 AE signals (Fig. 9) for all series specimens are also similar (18.99– 14.05 [μV·s]), for B-5 specimens, however, the value is slightly higher.

5. Conclusions

- The presented results confirm that the IADP acoustic emission method makes it possible to identify record, track and analyse the destructive processes that occur in unloaded early-age concrete.
- It can be assumed that the unit energy of AE signals for Class 1, 2 and 3 of destructive processes is constant over the 28 days period. This energy is almost an order of magnitude different from that of the subsequent signal classes (Class 1, 2, 3), which makes it possible to unambiguously identify classes which accompany destructive processes that develop (Figs 8, 9, 10).
- The destructive processes that arise in early-age concrete can be assigned to AE signal classes in accordance with the adopted classification scheme:
  - Class 1 - Microcracks in the cement paste
  - Class 2 - Microcracks at the aggregate-paste interface
  - Class 3 - Formation of microcracks on concrete surface
- For such thermal loading program Class 4 signals (growth of microcracks) were not observed as well as microcrack growth on specimens surface. Probably it is due to uniform temperature distribution on the specimens surfaces. Class 4 signals were identified in the case of significant temperature heterogeneity on these surfaces.

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