The Use of Acoustic Emission Method in the Modern Construction

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Abstract. The method of acoustic emission is a very effective NDT method, which is widely used in nuclear power, oil, gas and chemical industry, mining and health care. The method of acoustic emission is widely used and standardized in many countries. In the modern construction of the method of acoustic emission finds wide application in non-destructive testing and evaluating the condition of building structures. The goals of this report are review of the regulatory standards and perspective investigations on the application of the acoustic emission method in modern construction and present results of several scientific researches on this topic. The main provisions of the report will be presented in accordance with the following content: current state of standards and guidelines on acoustic emission in the construction field, comparative analysis and prospects; the results of research conducted by authors in the Research, Design and Technological Institute for Concrete and Reinforced Concrete named after Gvozdev and practical experience of application of the obtained results. Civil construction buildings form a class of the test objects, for which the estimates of the structural integrity by acoustic emission method can become a successful commercial application.

Introduction

Standards play an important role in the summarization of research results and development of cooperation in intellectual, scientific, technological and economic areas. Russia's accession to the World Trade Organization requires the introduction of international standards as an effective tool to improve the safety level of life and health of citizens, property of individuals and legal entities, and state and municipal property. Analysis of some standards and guidelines on application of acoustic emission (AE) method, published by the international, national and regional standards organizations, as well as activities of nonprofit organizations, allows us to estimate the current state of standardization and identify key areas where AE method is used, and to establish long-term directions for its future use. The analysis shows that the AE method is widely used in many countries around the world in various industries, research investigations and is widely standardized. The

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standards development organizations as to their status can vary from international (ISO, RILEM), regional (CEN, EWCAE), and national (AAR, ASTM, ASME, ANST, AFNOR, DGZfP, IEEE, JIS, Rosstandart) organizations to working groups in institutes and industry organizations whose documents are generally recommendatory. Table 1 presents data on the number and groups of AE standards developed by various international, regional and national organizations.

Table 1.

Organization	Full number of documents	AE terminology and definitions	General provisions on AE method use	Technique for measurement and calibration of AE sensors	Fields of application and specific techniques for AE method use	Application in construction
ASTM	28	1	3	7	17	0
ISO	4	1	0	2	1	0
CEN	6	1	2	2	1	0
EWGAE	5	1	1	1	2	0
AENOR	6	1	2	1	2	0
DGZfP	4	1	0	3	0	0
Rosstandart	12	1	6	2	4	0
RILEM						3
JIS						2

Most commercial applications of the AE method were and will remain procedures of testing of tankers and vessels for transportation and storage of petroleum products, storage tanks for liquefied gas, pressure vessels and pipelines for transportation of hydrocarbons. In construction industry the AE method is used widely enough [1-5]. Unfortunately the gained experience is not adequately reflected in the AE standards. As we know, today there are only 3 legal documents for the AE method application in construction [6-8]. Numerous studies in the construction using the AE method for nondestructive testing show perspective of this method. Construction and civil works (e.g., bridges, high-rise buildings, waterworks, nuclear power stations, etc.) constitute the class of objects for which assessment of structural integrity with the use of AE method can become commercially successful application. This paper examines new engineering applications of the AE method, which can be successful in construction.

Statistical Criterion

The usage of the AE method is a promising direction of the short-term, long-term or regular monitoring of the technical condition of complex industrial facilities and production equipment. INTERUNIS Group, NIIZhB named after A.A. Gvozdev and Bauman Moscow State Technical University (BMSTU) have developed the technique that allow to assess the technical condition of structures according to AE measurements and determining in advance a destructive stage of structural behavior. Statistical criterion [9-10] and algorithm of building structures assessment were used for determining a destructive stage.

The algorithm for computing the statistical criterion provides for formation of a sample of the flow of AE impulse parameters. An informational parameter of AE impulse is sampled, as well as conditions by which samples are formed. Samples are formed either to a specified number of the recorded AE pulses, or to the specified time interval Δt. On the basis of the sample of AE pulse parameters, distribution histograms are built from which statistical characteristics of distribution are computed (such as an average value, mode, dispersion, etc.). The next stage of computations is a normalization of sample values and computation of normalized entropy. As an example let us consider the computation of entropy of amplitude distribution. Normalization of AE pulse amplitude values in the sample allows for obtaining an amplitude probability density in the sample:

$$y_i = \frac{N_{Ai}}{\sum_{k=1}^{N_h} N_{A_k}}, \quad i = \overline{1, N_h} \tag{1}$$

Using (1), we obtain the normalized entropy S^H:

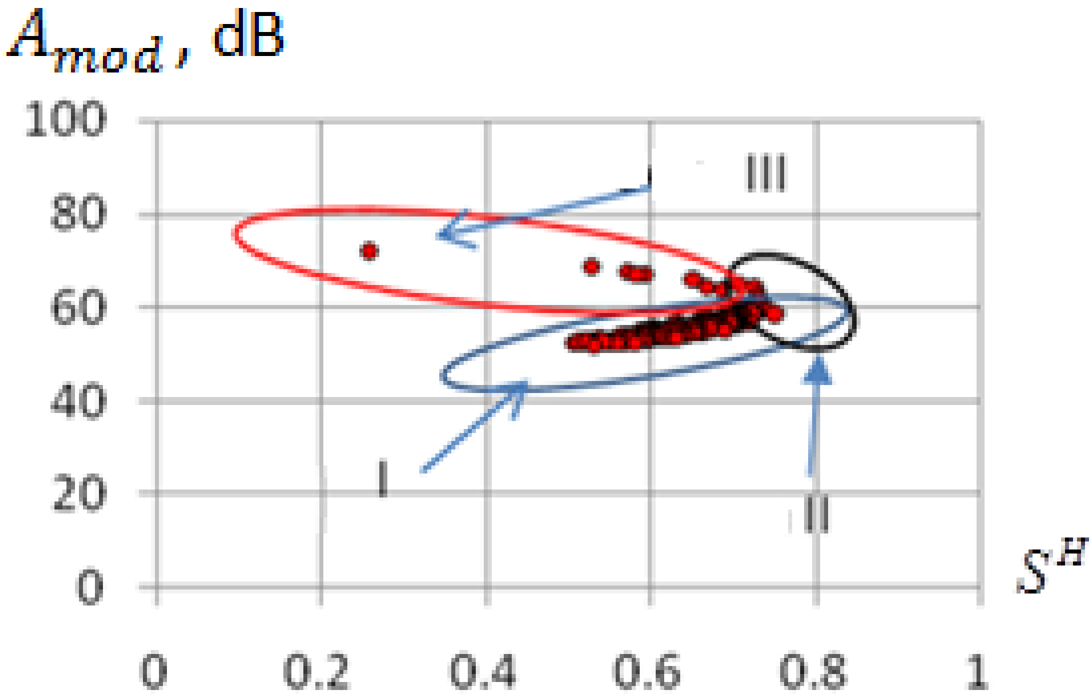
$$S^H = -\frac{\sum_{i=1}^{N_h} y_i \ln y_i}{\ln N_h} \tag{2}$$

Normalization of the amplitude distribution entropy causes that its values are from 0 (minimum chaos) to 1 (maximum chaos).

The investigations conducted in reinforced concrete structures have shown, that the following relationship can be selected as an identification parameter:

$$F_{par} = A_{mod}(S_A^H), \tag{3}$$

where F_{par} is a dependence of the mode A_{mod} of AE signal amplitudes on the relative entropy S_A^H of this distribution. The mode is the commonly occurring values of amplitudes in the sample.

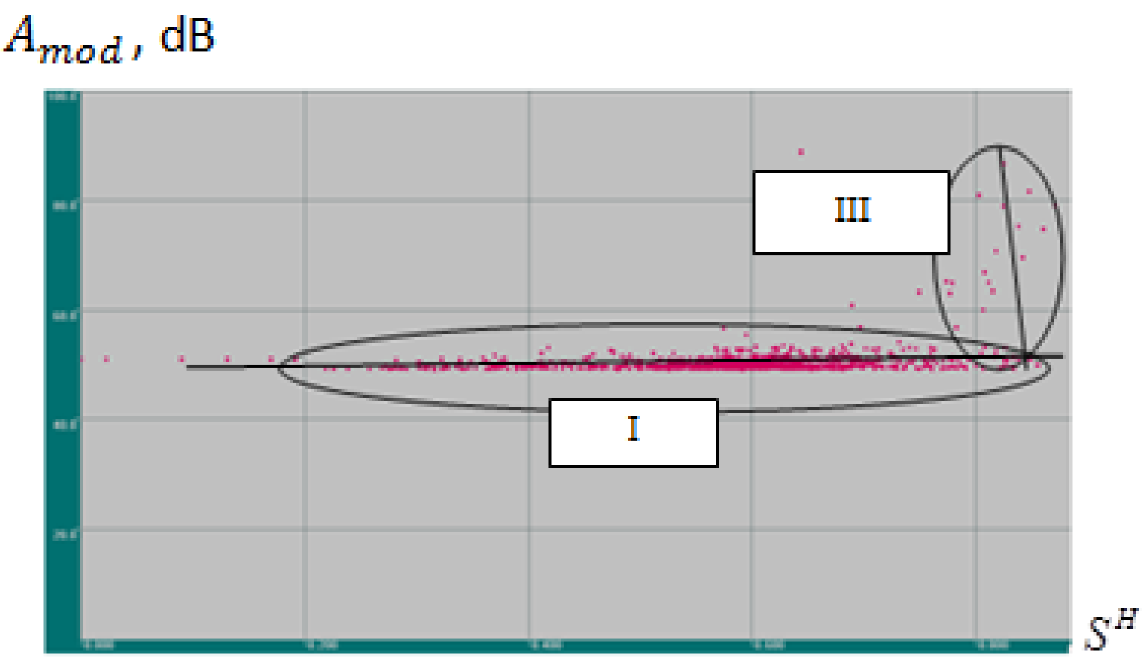


Pic.1. Dependence of the mode A_{mod} of AE signal amplitudes on the relative entropy S_A^H of this distribution

As an example, results of application of the statistical criterion for estimating of condition of a pre-stressed concrete beam are given below. The beam was made of self-stressing concrete with compressive strength class B45. Portland cement-M500 produced by the Stary Oskol plant was used as a cementing component. The self-stressing concrete was prepared by mixing Portland cement and a concrete expanding additive made according to the Russian industry specification OTU 46854090-98. Granite macadam of 5-20 mm fraction and sand of fineness modulus 2.2 mm were used as aggregates. Reinforcing bars were placed in the beam lower part. Prestressed reinforcement of A-V class and diameter 16 mm was used. Reinforcement pretensioning was carried out by means of hydraulic jacks using a pump station. AE sensors were mounted on the beam side surface by means of wax-rosin compound. Acoustic contact between the AE sensor and concrete was provided with a contact lubricant. Loads to beams were applied by a hydraulic jack and a manual pumping station. Localized application of jack loading was carried out through a stiffening distributive cross tie to the beam at 2 points located at the distance of 520 mm from ends. The beams were pivotally rested on 2 supports. The distance from beam ends to supports was 150 mm. For the load application mode a step mode was accepted. The value of loading step was 10 to 15 % of the breaking load. The sample was carried to failure. The diagram, constructed according to the beam testing data (Pic. 1), shows the numerical values of (3) located in 3 clusters: I, II and III. Cluster I is a representative for the most stages of beam loading. Formation of normal or diagonal force cracks with an opening width up to 0.25 mm and increase in beam deflection do not substantially change the manner of arrangement of numerical values in Cluster I. Growth of the cracks and increase in the beam deflection are characterized by increase in the amplitude of signals. Before destruction (stress level in beam being 0.94-0.95 of breaking force) cluster II appears. At this stage, main cracks appear in the structure, and beam deformations grow nonlinearly. Cluster III corresponds to the predestruction stage when the structure has not yet destroyed, but there is a further increase in the main cracks, the crack opening width exceeds 0.3 mm, and the concrete compressive zone fails, further nonlinear deformations of the beam takes place. Sequential transition from cluster I to cluster II and then to cluster III is characterized by changing the angle of linear relationship (3). Thus, if the mode A_{mod} increases with the increasing of entropy S_A^H (cluster I), it is possible to talk about the serviceable state of structure, but if the mode A_{mod} decreases with the increasing of entropy S_A^H (cluster III), the structure is near failure.

Pic. 2. Experimental sample made as a section of a floor slab and columns.

A floor slab was also tested for punching shear strength. The slab was additionally strengthened against punching shear with a use of transverse reinforcement. The experimental sample was made as a section of a floor slab and columns (bottom and top). 24 metal studs were used for strengthening the floor against punching shear in the column area. The studs were installed into through-holes which were pre-drilled using a diamond-point bit. The studs were arranged as a cross (Pic. 2). The distance between the column edge and the first row of studs was 50 mm, the spacing of subsequent rows was 50 mm, and the distance between half-lines was 100 mm. The transverse reinforcement was made of M10 thread studs of steel grade 8.8. The studs were anchored with grade 8.8 nuts and washers of size 40x40x6 mm. To involve the transverse reinforcement into work, the studs were preliminary tightened using a torque wrench. Load was transmitted to the slab through metal pull rods passed through the working holes in the slab. The pull rods were pivotally fastened to the power floor. Load in the sample was made by a hydraulic jack mounted below the column. Indicating gages were used to measure deformations. AE measurements were performed by 8 channel AE system A-Line 32D manufactured by INTERUNIS Group. 5 AE sensors, having the frequency range of 30-300 kHz, were mounted onto the upper surface of the slab. The first cracks in the sample appeared around the edges of columns at the loading steps equal to 0.2-0.3 of breaking force. At loads 0.3-0.4 of breaking force radial cracks formed from the edges of columns and propagated to the slab outer sides. In the outermost samples at loads equal to 0.4-0.5 of breaking loads inclined cracks were formed near the edges of columns. At the limit stages the largest opening of cracks were observed around the column edges, and the width of cracks was from 2 to 2.5 mm. Pic. 3 shows the results of experimental data processing. Cluster I is typical for most of the steps of sample loading. AE signals actively appeared during the whole experiment. The most of signals corresponds to the range of entropy S_A^H from 0.5 to 0.7. Before failure (loading level in the sample is 0.94-0.96 of breaking force) cluster II appears. At this step main cracks appear in the structure, and deformations in the floor slab grow nonlinearly. Cluster III corresponds to a predestruction stage.



Pic. 3. The testing of a floor slab.

Strength of hardening

Another promising field of AE application is nondestructive testing of concrete strength by the AE method. The concrete strength is one of the important characteristics of material. The concrete strength is controlled by various methods: compression-bending test of samples made during structure concreting, selection and subsequent testing of structure segments, non-destructive methods of testing, testing of concrete strength by the concrete temperature. In NIIZhB a series of experiments was carried out, aimed to develop technique for testing the strength of hardening concrete using the AE method. The necessity to develop such a technique is dictated by engineering problems arising in determining the stripping strength of concrete and on-line decision-making whether the supplied concrete mix meets the design requirements.

Experiments were carried out on cubes of size 200x200x200 mm. A mold for cubes was made of plywood. 2 round holes of diameter 30 mm were cut in the mold walls on each side. Metal plates were fixed on the inside and outside of the mold. From the inside the plate was flat, while from the outside the metal plate had a hole of diameter 30 mm, and this plate was intended for fixing a magnetic holder. AE sensor by means of the magnetic holder through a layer of contact lubricant was mounted to the outer metal plate. Each concrete composition was provided with an auxiliary set of samples of cubes having a size of 70x70x70 mm.

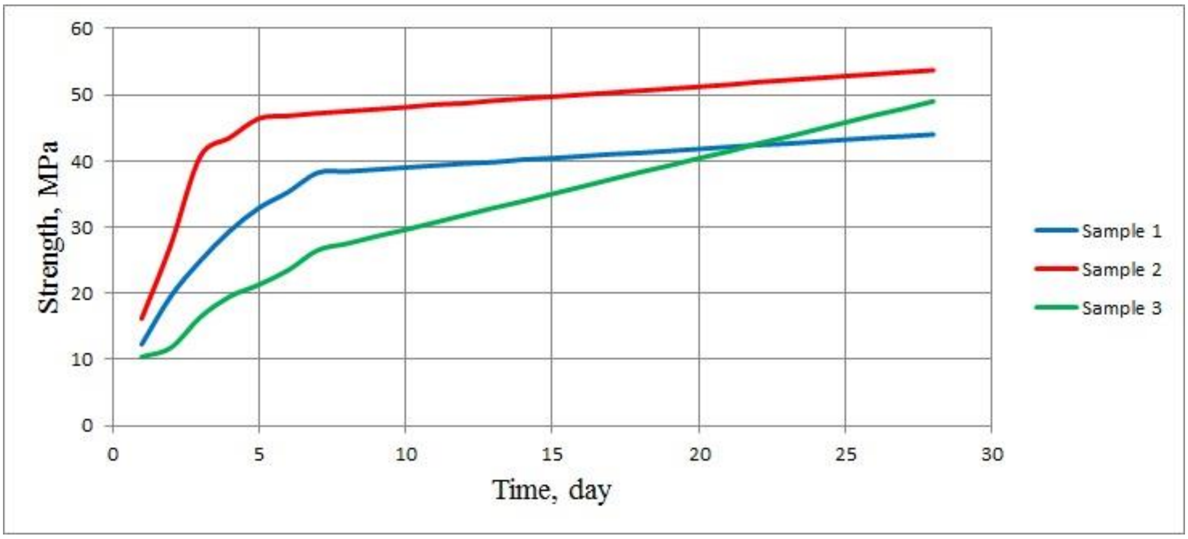
The concrete samples were distinct in composition and strength (Table 2). To prepare concrete, glass sand with a fineness modulus of 3-4 mm, granite macadam with the fineness modulus of 20-35 mm and cement from the Voskresensky plant, grade 500, without additives were used. The concrete mix was compacted at a vibrating plate.

Table 2. Compositions, used for preparation of the concrete cubes.

Nunber of sample	Per 1 m^3 of concrete			
	Cement, kg	Glass sand, kg	Granite macadam, kg	Water, l
Sample 1	350	740	1100	180
Sample 2	475	810	1075	170
Sample 3	380	740	1100	160

A-Line 32D 8-channel AE system manufactured by INTERUNIS Group was used. The following settings of system operating were adopted: sampling frequency – 2000 kHz; maximum duration – 2000 μs; pretriggering – 250 μs. 3 AE sensors, having the frequency range of 30-300 kHz, were used. AE signals were monitored continuously for 42 days.

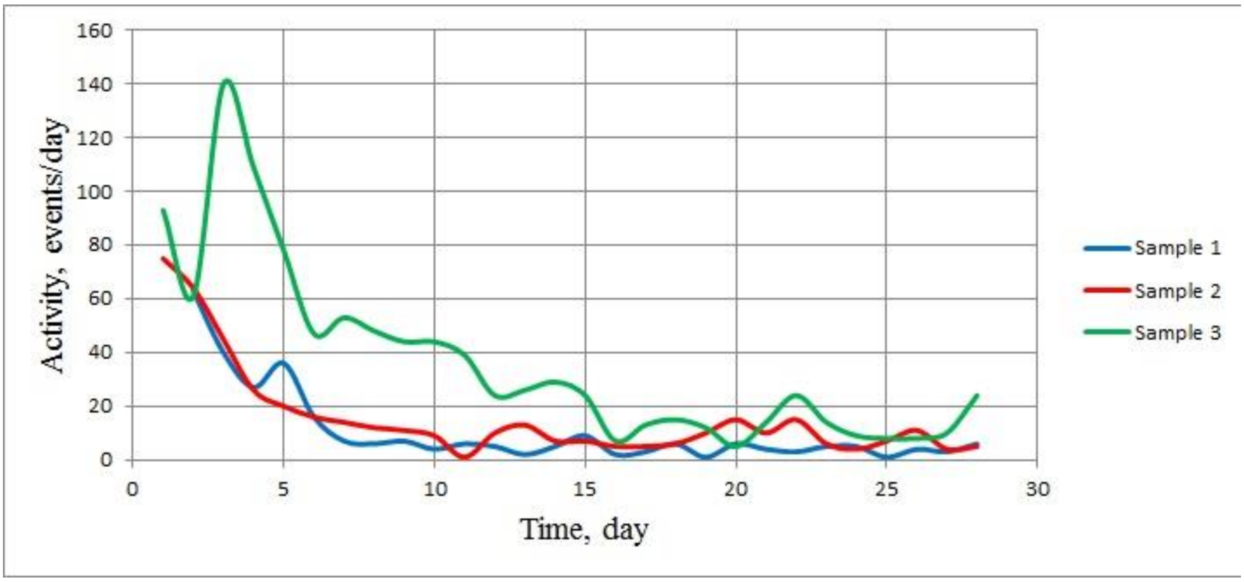
During the experiment, the instantaneous strength of concrete was measured regularly (Pic. 4). It has been found that the concrete structure is formed for a long time.



Pic. 4. Instantaneous strength of concrete.

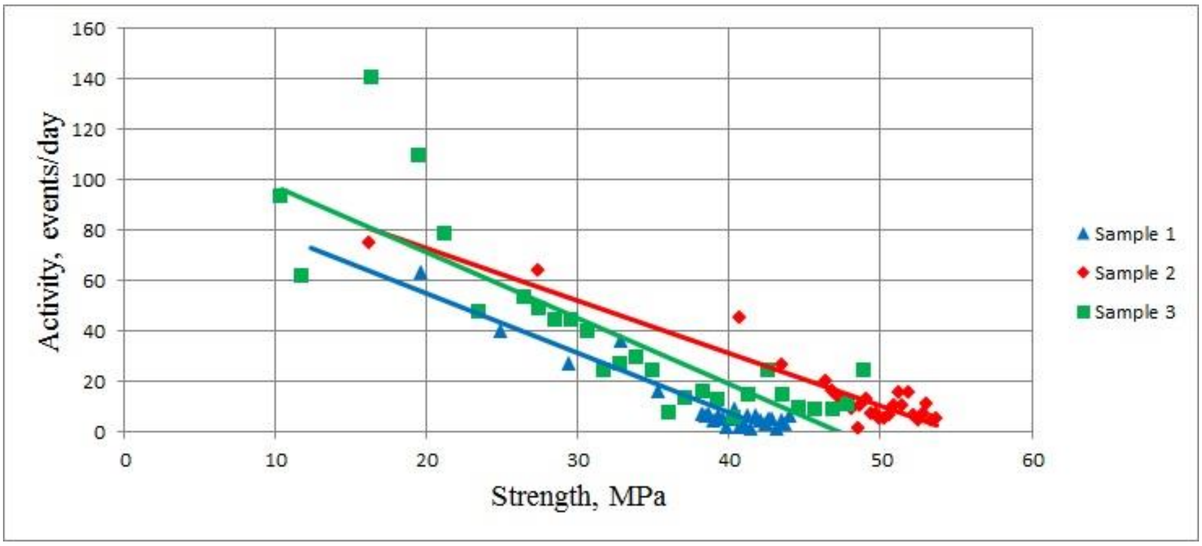
The acoustic emission was registered during the whole experiment (Pic. 5). The first AE signals in the concrete mix were recorded immediately after mix preparation. Completion of intensive development of the concrete strength (5th day of hardening) is characterized by lower activity of AE signals.

The average energy of AE signals, the average amplitude, the activity of AE signals, the mean value of AE signal rise time and the mean duration of AE signal were used as the statistical parameters of AE signals (Pic. 5).



Pic. 5. Activity of AE signals.

The conducted investigations have shown a close correlation between the activity of AE signals and instantaneous concrete strength (Pic. 6). The correlation coefficient is from 0.8 to 0.99.



Pic. 6. The correlation between activity and instantaneous concrete strength.

Thus, analysis of these investigations shows that the AE method can be used for determination the concrete strength rise during the process of its hardening.

Conclusions

1. INTERUNIS Group and NIIZhB have developed the technique and algorithm that allow to estimate the technical condition of structures according to the AE data and determine in advance the destructive stage of structural behavior.
2. Concrete hardening is accompanied by AE signals. The conducted investigations and their analysis show that the AE method can be used for monitoring the concrete strength rise during the process of its hardening.

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