Scientific Review – Engineering and Environmental Sciences (2019), 28 (3), 356–365
Sci. Rev. Eng. Env. Sci. (2019), 28 (3)
Przegląd Naukowy – Inżynieria i Kształtowanie Środowiska (2019), 28 (3), 356–365
Prz. Nauk. Inż. Kszt. Środ. (2019), 28 (3)
http://iks.pn.sggw.pl
DOI 10.22630/PNIKS.2019.28.3.33

Aleksandra KRAMPIKOWSKA, Anna ADAMCZAK-BUGNO
Faculty of Civil Engineering and Architecture, Kielce University of Technology

Assessment of the technical condition of prefabricated elements using the acoustic emission method

Key words: acoustic emission, diagnostic method, prestressed beams, durability

Introduction

The problem of diagnostics and monitoring of the technical condition of concrete elements is a very up-to-date and socially important subject. The aging infrastructure and increasing operational burdens of engineering structures are the main stimuli for fast-progressing research on the new interdisciplinary field of technical knowledge called structural health monitoring (SHM). This issue is closely related to the durability and time of safe operation of structural elements.

Durability should be understood as the period counted in years in the course of which a given object or part of it retains its useful properties under normal operating conditions (Świt, 2009, 2018).

The durability of the individual elements of the structure and finishes determine the durability of the object. The durability of an object depends on many factors, i.e. on the quality of workmanship and the way of using its individual elements, on the type and quality of material, production technology, unfavourable influences of the external environment (Goszczyńska, Świt & Trąmpczyński, 2016). On the other hand, repairs are understood as the execution of construction works in an existing building, consisting in reconstruction of the original condition, which do not constitute ongoing maintenance, although it is allowed to use construction products other than those used in the original condition (Goszczyńska, Świt & Trąmpczyński, 2014).

In the current principles of designing structural elements (based mainly on the load capacity as the basic required parameter), the goal was to achieve the required functionalities using the lowest possible financial resources for implementation. The durability of the facility in this case was limited to the construction period or up to several years of the warranty period after the construction was completed.

The impact of material degradation on the durability of concrete elements is difficult to estimate. There are many methods of construction diagnostics measuring individual parameters, but usually only at the moment of performing the inspection. Therefore, the obtained results show the current state of the structure, however, we cannot say anything about the dynamics of destructive processes in the time frame, which would make it easier to estimate the durability of concrete elements with a selected statistical model.

Work is underway on the creation of a SHM all over the world, so that damage and defects are detected in advance.

Early detection of defects and appropriate methods of repairing and strengthening them will help to prevent damage to the structure (Proverbio & Venturi, 2005; Goszczyńska et al., 2014; Goszczyńska et al., 2016). This will save money spent on maintenance or repairs and ensure the safe operation of the structure throughout their lifetime. Due to the aging of the construction infrastructure, there is a need to develop and implement a diagnostic technique suitable for continuous monitoring and assessment of durability of concrete elements. This issue is a priority in research for infrastructure managers performed by engineers and scientists.

The methods used in SHM are aimed at locating damage to the structure, assessing their intensity and possible forecasting of safe operation time or making a decision to renovate or replace the damaged element.

The non-destructive testing (NDT) emission diagnostic methods only reveal damage covered by a penetration beam (e.g. a ray of ultrasonic waves) and can be carried out in a limited volume (Pascale, Leo & Bonora, 2003; Rens, Nogueira & Transue, 2005). Therefore, it is difficult to preserve their representativeness, especially for the entire structure, where a number of places are difficult to access and they may be outside the area of the research ray (Rens & Kim, 2007). It should also be noted that the current system of assessing the technical condition of the components of the structure being examined, theoretically is performed using the same or similar criteria (Yehia, Abudayyeh, Nabulsi & Abdelqader, 2007), however, depends to a large extent on the persons performing the tests and their practical experience in interpreting the results (Pascale et al., 2003). Additionally, the measurement results obtained during the tests are insufficient to assess the actual bearing capacity of the concrete elements under evaluation, their durability forecasting and the optimal time and scope of repairs, which increases their maintenance costs (Rens & Greimann, 1997; Yehia et al., 2007; Sharma & Mukherje, 2011).

In the case of prestressed concrete constructions, one can distinguish the following destructive processes that are also sources of acoustic emission – AE (Lee, Lee, Kim & Bea, 2004; Hsieh, Halling & Barr, 2006; Świt, Krampikowska & Minh Chinh, 2016; Świt, Adamczak-Bugno & Krampikowska, 2019a, 2019b).

- microcracking;
- friction between the surfaces of cracks;
- formation and development of cracks in concrete;

- cracking at the border of concrete reinforcement;
- concrete crumbling;
- friction at the border of reinforcement;
- corrosion;
- plastic deformation and cracking of cables and other reinforcements.

The values of the parameters of the registered AE signals allow to group signals into classes, each of which characterizes other dominant destructive processes (in accordance with the above-mentioned classification) and a different degree of danger to the structure (Paulson & Dwit, 2003; McCarter & Vennesland, 2004; Goszczyńska, Świt & Trąmpczyński, 2015). The signals characteristic for each class create "reference" databases enabling identification of the destruction process, e.g. "cracking at the border concrete – reinforcement" corresponds to a database that groups selected signal parameters assigned to this process.

Databases for individual processes (or their groups) are determined on material samples, models in special laboratory tests (where a given destructive process or a group of processes predominates) and on full-size structural elements during endurance and attestation tests as well as during normal operation of objects.

Having the database of AE reference signals, one can identify active destructive processes occurring in the entire tested element/structure volume (Świt, 2004; Minh Chinh, Adamczak, Krampikowska & Świt, 2016; Olaszek, Świt & Casas, 2016; Świt, Krampikowska & Minh Chinh, 2016; Świt, Krampikowska, Minh Chinh & Adamczak, 2016). By carrying out measurements for a longer time, it is possible to determine the damage development under real load conditions taking into account external conditions such as rain, frost or wind. Proper placement of the AE sensors allows for the measurement of the entire examined element and the location of the emission source (the place of destruction).

The NODSIS 5.8 program, using hierarchical, non-hierarchical statistical grouping methods and neural networks, was used to build the reference signal base in the RPD method (development of destructive processes) (Nagy, 1997; Świt, 2009; Goszczyńska, Świt & Trąmpczyński, 2013). In the case of the RPD method base, the pattern recognition method was used (Goszczyńska et al., 2015), in two versions: with arbitrary division into classes (unsupervised) – USPR and self-learning, in which the division into classes took place using reference signals (supervised) – SPR (Goszczyńska, Świt, Trąmpczyński, Krampikowska, 2010; Goszczyńska, 2014).

Creating a signal base is a complicated process that requires a lot of resources and inventiveness (Goszczyńska et al., 2013; Goszczyńska, 2014; Goszczyńska et al., 2015).

The created base of reference signals is composed of 8 classes marked with the symbols and colours assigned to them, as shown in Table 1.

Class numbers mean (Goszczyńska et. al., 2010; Goszczyńska, 2014; Goszczyńska et al., 2015):

- No. 1. Microcracks in concrete on the border of the aggregate fraction with dimensions 0–2 mm;

TABLE 1. Classes and codes of AE signals

Colour	○	□	◆	▼	▲	●	+	X
Number of class	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8

- No. 2. Microcracks in concrete on the border of the aggregate fraction of 2–8 mm;
- No. 3. Formation and propagation of scratches in the stretched concrete zone;
- No. 4. Development of scratches and friction on the border of the aggregate fraction with dimensions above 8 mm;
- No. 5. Yielding of steel;
- No. 6. Cracking at the border of concrete – reinforcement;
- No. 7. Separation of reinforcement from concrete;
- No. 8. The breaking of prestressing strands.

Materials and methods

As part of the research work, three T-27 prestressed concrete beams were tested during their production process: concreting and heating. During the tests, using the 24-channel μSAMOS processor, preamplifiers and 11 sensors with flat frequency response in the range of 30–80 kHz, acoustic emission signals generated during the beam generation process were recorded.

The tests were carried out on prestressed concrete beams with 26 weaves 7ø5 mm placed in the bottom part of the beam, two strands 7ø5 mm in the zone connecting the web and shelf, and soft reinforcement arranged in accordance with Figure 1, made of C40/50 class concrete on basalt aggregate.

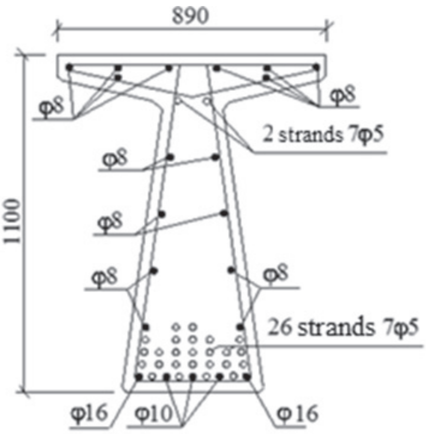


FIGURE 1. Cross-section of the beam along with the distribution of reinforcement

The stand for testing the prestressed concrete beam with the location of the AE sensors is shown in Figure 2. During concreting with each batch – the volume of concrete in the beam was 11.2 m^3.

Results and discussions

The average compressive strength of the concrete cubic samples taken from the trial batch used for production of beams after 28 days of maturation was 40.05 MPa. During the study, the spread of compressive strength results was found from 21.75 to 91.57 MPa. Such a large spread indicates the heterogeneity of the concrete mix and has a large a)

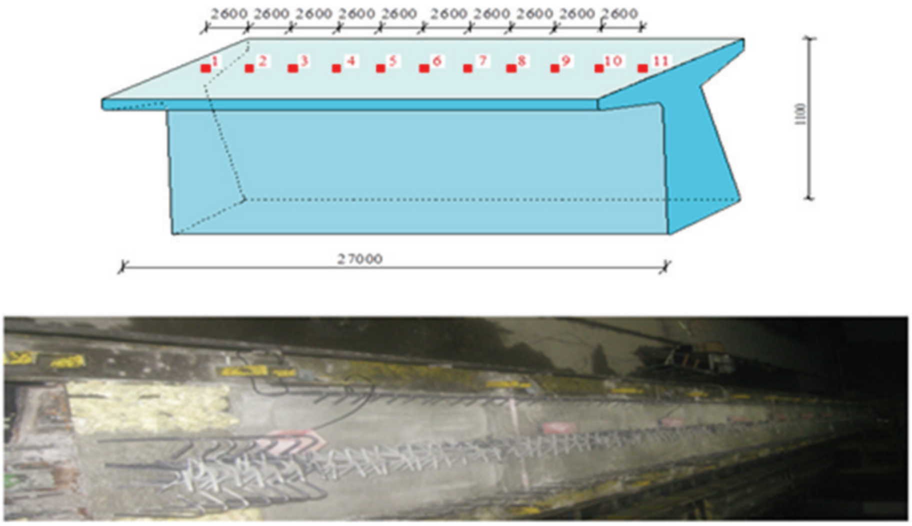


FIGURE 2. Research position: a – scheme of the beam loading station with the location of the sensors; b – view of a pre-stressed concrete beam subjected to heating together with installed acoustic emission sensors

impact on the damage (shrinkage cracks) as well as on further functional values, i.e. load capacity and durability. The stages of concrete damage during the compression test are shown in Figure 3.

When squeezing concrete samples, one more sensor with a flat characteristic in the range of 30–80 kHz and a preamplifier was installed on their surface, which recorded the acoustic signals ac-

FIGURE 3. Stages of destroying concrete samples subjected to compression

companying the destruction of the sample in the compression test. The registration of these results was caused by the need to supplement the base of reference signals forming the pattern in the RPD and IADP method, with data from the destruction of concrete samples of two classes of bridge concrete. The aggregate measurement results of AE signals generated during testing of 8 concrete samples with different strengths are shown in Figure 4.

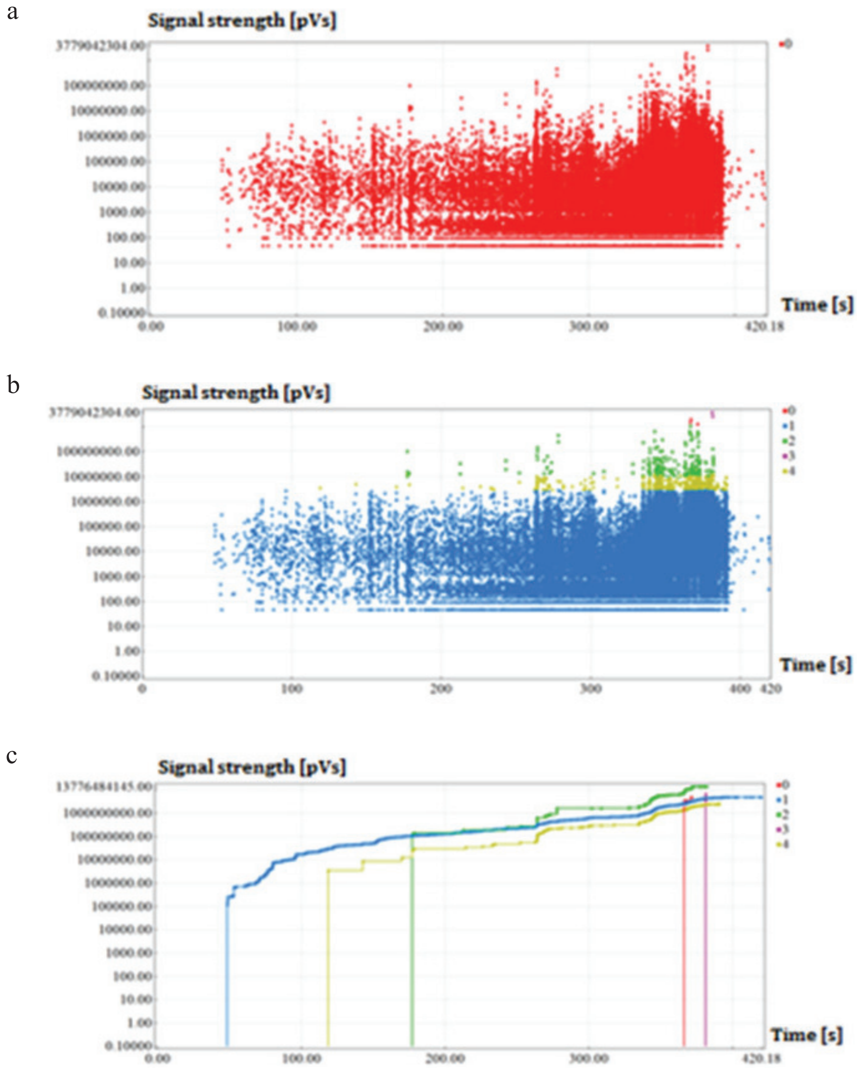


FIGURE 4. AE signals recorded during a compression test: a – AE spot power signal plotted versus time without statistical analysis; b – AE spot power signal versus time diagram is subjected to statistical analysis using the k-means method; c – AE power signal summation graph as a function of time subjected to statistical analysis using the *k*-means method

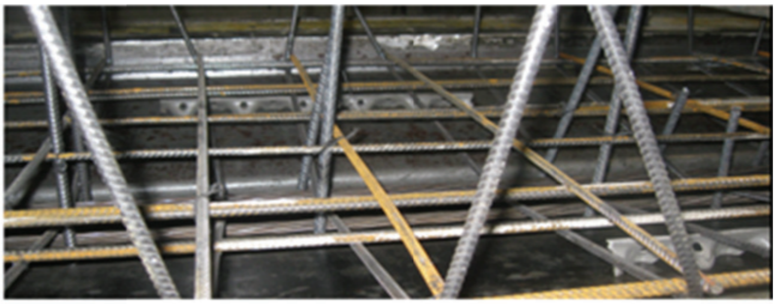
Analysing the results of the AE method, it can be seen (Fig. 4a) how difficult it is to conclude about the destructive processes accompanying the destruction of concrete by observing the raw measurement data. We can only determine the value of the tested parameter, possibly assess the stability and intensity of the changes taking place.

However, when analysing the same AE data (Fig. 4b), but treated by statistical methods of grouping signals, in this case the *k*-means method, it can be noticed that during the compression process of concrete samples, five signal classes can be distinguished, which can be pre-assigned to processes generating them. It is worth noting (Fig. 4c) that the statistical processing of signals and the summation chart allows to determine the moment of initiation of individual failure mechanisms, which is extremely important for the assessment of the progress of these processes and their impact on the durability and load-bearing capacity of the tested items.

After basic strength tests and contraction phenomena on concrete samples, acoustic emission measurements were carried out on the actual construction element, namely the T-27 prestressed concrete beam. Measured signals were generated by various phenomena, during accelerated maturation of concrete caused by heating. An example of structural reinforcement and passive reinforcement is presented in Figures 5a and 5b.

During this process, 12 AE parameters were recorded with sensors arranged as in Figure 2. As a result of the high temperature of +65 ±2°C and the binding and shrinkage processes occurring in the

a



b

FIGURE 5. Arrangement of reinforcement in T-27 pre-tensioned concrete beam

concrete mix, AE signals were recorded, which were then subjected to analysis of the reference signal database developed for the RPD method and enriched with the results of tests on shrinkage and compression samples. The results of this analysis are presented in Figure 6.

It is worth noting that if we do not have the localization option in the software used to record AE signals, using (Fig. 6a) of the graph of any AE parameter as a function of the recording channel allows us to determine the approximate coordinates of the appearance of the defect on the tested element, which is extremely important in the assessment technical condition of these elements. In addition, using the analysis of AE signals based on a comparison with the base of reference signals (Fig. 6b), we can evaluate not only the intensity of appearing AE signals, but also determine the mechanisms generating them (Figs. 6c and 6d). What is important when assessing their further impact on the durability and/or load bearing capacity of the tested concrete element.

Conclusions

Analysing the results of the research, it can be concluded that the application of the acoustic emission method using the base of reference signals and the functions locating the place of gen-

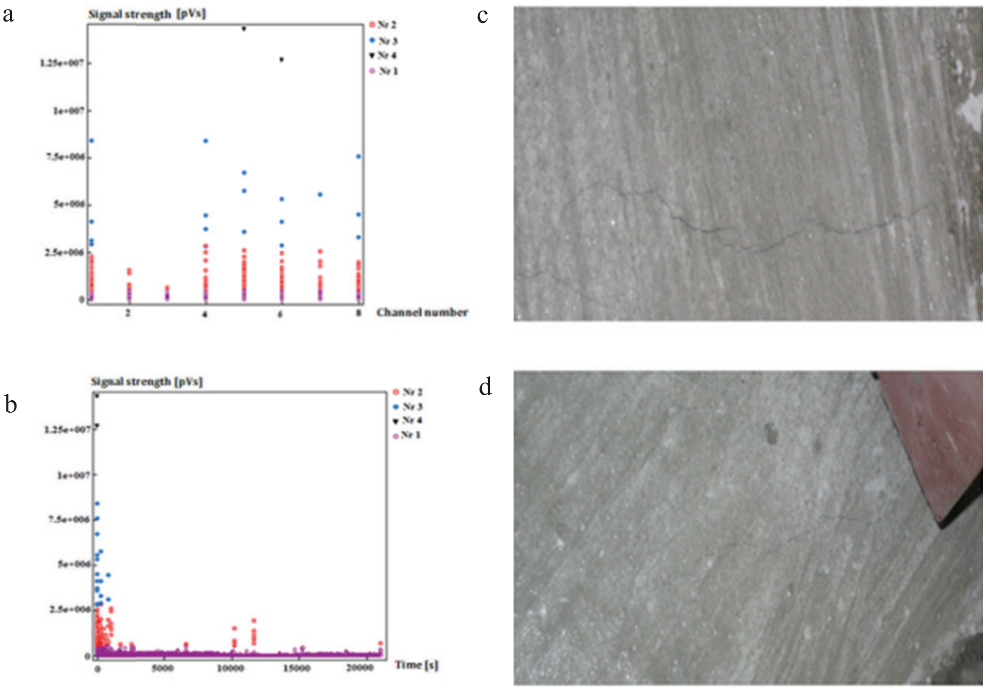


FIGURE 6. AE signals registered in the process of supporting the maturing of concrete by heat treatment: a – AE signal power spot diagram as a function of the recording channel; b – AE spot power signal versus time diagram; c – a 0.1 mm wide crack within sensor 5; d – a crack width of 0.1 mm within sensor 6

erating destructive processes is helpful in assessing the course of the occurring mechanisms causing damage to the examined concrete element. It is possible to confirm the full usefulness of this tool to determine the processes generating the formation of scratches and cracks, which in turn will contribute to predicting the durability of the examined elements based on statistical data measured in situ and stored as so-called construction (element) passport. This is one of the basic assumptions of the system for assessing the durability of concrete elements and forecasting its durability.

References

Goszczyńska, B. (2014). Analysis of the process of crack initiation and evolution in concrete with acoustic emission testing. *Archives of Civil and Mechanical Engineering*, *14*(2), 134-143.

Goszczyńska, B., Świt, G. & Trąmpczyński, W. (2013). Monitoring of active destructive processes as a diagnostic tool for the structure technical state evaluation. *Bulletin of the Polish Academy of Sciences, Technical Sciences*, *61*(1), 97-109.

Goszczyńska, B., Świt, G. & Trąmpczyński, W. (2014). Assessment of the technical state of large size steel structures under cyclic load with the acoustic emission method – IADP. *Journal of Theoretical and Applied Mechanics*, *52*(2), 289-299.

Goszczyńska, B., Świt, G. & Trąmpczyński, W. (2015). Analysis of the microcracking process with the Acoustic Emission method with respect to the service life of reinforced concrete structures with the example of the RC beams. *Bulletin of the Polish Academy of Sciences: Technical Sciences*, *63*(1), 55-65.

Goszczyńska, B., Świt, G. & Trąmpczyński, W. (2016). Application of the IADP acoustic emission method to automatic control of traffic on reinforced concrete bridges to ensure their safe operation. *Archives of Civil and Mechanical Engineering*, *16*(4), 867-875.

Goszczyńska, B., Świt, G., Trąmpczyński, W. & Krampikowska, A. (2010). Application of the acoustic emission (AE) method to bridge testing and diagnostics comparison of procedures. *IEEE Xplore - IEEE Proceedings,* 1-10.

Hsieh, K.H., Halling, M.W. & Barr, P.J. (2006). Overview of vibrational structural health monitoring with representative case studies. *Journal of Bridge Engineering*, *11*(6), 707-715.

Lee, H.K., Lee, K.M., Kim, Y.H. & Bea, D.B. (2004). Ultrasonic in-situ monitoring of setting process of high performance concrete. *Cement and Concrete Research*, *34*(4), 631-640.

McCarter, W.J. & Vennesland, R. (2004). Sensor systems for use in reinforced concrete structures. *Construction and Building Materials*, *18*(6), 351-358.

Minh Chinh, L., Adamczak, A., Krampikowska, A. & Świt, G. (2016). Dragon bridge - the world largest dragon-shaped (ARCH) steel bridge as element of smart city. *E3S Web of Conferences*, *10*, 1-5.

Nagy, A. (1997). Determination of E-modulus of young concrete with nondestructive method. *Journal of Materials in Civil Engineering*, *9*(1), 15-20.

Olaszek, P., Świt, G. & Casas, J.R. (2016). On-site assessment of bridges supported by acoustic emission. *Proceedings of the Institution of Civil Engineers – Bridge Engineering*, *169*(2), 81-92.

Pascale, G., Leo, A.D. & Bonora, V. (2003). Non--destructive assessment of the actual compressive strength of high-strength concrete. *Journal of Materials in Civil Engineering*, *15*(5), 452-459.

Paulson, P.O. & Dwit, M. (2003). The use of acoustic monitoring to manage concrete structures. In *Proceedings of the International Non-Destructive Testing in Civil Engineering Symposium*, *8* [CD].

Proverbio, E. & Venturi, V. (2005). Reliability of nondestructive tests for on site concrete strength assessment. In *International Conférence On Durability of Building Materials and Components*, Lyon 17-20.04.2005.

Rens, K.L. & Greimann, L.F. (1997). Ultrasonic approach for nondestructive testing of civil infrastructure. *Journal of Performance of Constructed Facilities*, *11*(3), 97-104.

Rens, K.L. & Kim, T. (2007). Inspection of Quebec street bridge in Denver, Colardo: destructive and nondestructive testing. *Journal of Performance of Constructed Facilities*, *21*(3), 215-224.
Rens, K.L., Nogueira, C.L. & Transue, D.J. (2005). Bridge management and nondestructive evaluation. *Journal of Performance of Constructed Facilities*, *19*(1), 3-16.
Sharma, S. & Mukherje, A. (2011). Monitoring corrosion in oxide and chloride environments using ultrasonic guided waves. *Journal of Materials in Civil Engineering*, *23*(2), 207-211.
Świt, G. (2004). Evaluation of compliance changes in concrete beams reinforced by glass fiber reinforced plastics using acoustic emission. *Journal of Materials in Civil Engineering*, *16*(5), 414-418.
Świt, G. (2009). Diagnostics of prestressed concrete structures by means of acoustic emission. *IEEE Xplore – IEEE Proceedings*, *2*, 958-962.
Świt, G. (2018). Acoustic emission method for locating and identifying active destructive processes in operating facilities. *Applied Sciences*, *8*(1295), 1-20.
Świt, G., Adamczak-Bugno, A. & Krampikowska A. (2019a). Bridge management system within the strategic roads as an element of smart city. *IOP Conference Series: Earth and Environmental Science*, *214*(1), 1-9.
Świt, G., Adamczak-Bugno, A. & Krampikowska, A. (2019b). Application of the acoustic emission method in the assessment of the technical condition of steel structure. *IOP Conference Series: Earth and Environmental Science*, *214*(012055), 1-10.
Świt, G., Krampikowska, A. & Minh Chinh, L. (2016). A prototype system for acoustic emission-based structural health monitoring of My Thuan Bridge. *Proceedings of 2016 Prognostics and System Health Management Conference (PHM-Chengdu)*, 624-630.
Świt, G., Krampikowska, A., Minh Chinh, L. & Adamczak, A. (2016). Nhat Tan Bridge – the biggest cable-stayed bridge in Vietnam. *Procedia Engineering*, *161*, 666-673.
Yehia, S., Abudayyeh, O., Nabulsi, S. & Abdelqader, I. (2007). Detection of common defects in concrete bridge decks using non-destructive evaluation techniques. *Journal of Bridge Engineering*, *12*(2), 215-224.

Summary

Assessment of the technical condition of prefabricated elements using the acoustic emission method. The article presents the results of tests using the acoustic emission method during the formation process of T-27 prestressed concrete beams. The studies included two stages. The first – testing the compressive strength of the cubic samples taken from the trial batch used for the production of beams together with the acquisition of acoustic emission signals. The second – measurements by acoustic emission, on the actual construction element during accelerated maturation of concrete caused by heating. The undertaking of the above subject results from the fact that this issue is of great importance when assessing the durability of reinforced concrete and pre-compressed elements in the aspect of the analysis of these structures in terms of durability. The impact of material degradation on the durability of the structure is difficult to appraise due to the lack of reliable results needed to estimate the durability of the selected statistical approach. However, the use of the acoustic emission method based on the identification of destructive processes creates the possibility of locating, identifying and monitoring the emerging and developing destructive processes affecting the durability of concrete elements.

Authors' address:
Aleksandra Krampikowska
(https://orcid.org/0000-0002-1784-9989)
Anna Adamczak-Bugno
(https://orcid.org/0000-0003-3314-3801)
Politechnika Świętokrzyska
Wydział Budownictwa i Architektury
al. 1000-lecia Państwa Polskiego 7
25-314 Kielce
Poland
e-mail: akramp@tu.kielce.pl
aadamczak@tu.kielce.pl