Assessment of Destruction Processes in Fibre-Cement Composites Using the Acoustic Emission Method and Wavelet Analysis

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Abstract. In recent years, there has been a growing interest in fibre-cement boards as a finishing material for facades, internal walls and roofs. These panels, used in construction for over one hundred years, are made of natural ingredients such as cement, cellulose fibres and polyvinyl alcohol fibres (PVA), water and mineral fillers. It should be emphasized that due to the method of use, these elements carry loads of significant value as a result of wind pressure and suction. In addition, the boards are exposed to long-lasting atmospheric conditions such as rainfall, significant temperature fluctuations. The threatening factors also include the possibility of exceptional conditions, including fire. Long-term exposure to various types of conditions results in a significant reduction of the material's durability after only a few years of use. In connection with the above, it is considered that it is recommended to conduct research to assess the state of fibrous - cement elements exposed to the conditions, for which they will be exposed to during operation. The article presents the possibility of using the acoustic emission method (AE) and time-frequency analysis as tools for monitoring the state of cement-fibre boards. Three-point bending tests were carried out on air and dry samples, soaked for 1 h and 24 h. Acoustic emission signals were acquired during the tests. The obtained results allowed to follow the mechanisms of destroying the examined elements and to observe the influence of the conditions and their duration on changing the way of destroying the elements.

1. Introduction

The fibre cement boards used for over a hundred years have replaced the eternity boards, which were discontinued from production. They are healthy, environmentally safe materials. They consist mainly of Portland cement. The filler is cellulose fibres, while ensuring the right amount of water in the cement binding process. In addition, polyvinyl alcohol (PVA) fibres also use as reinforcement. In the production process, neutral fillers, such as limestone or mica also add to the mix [1-3]. During production, the board is formed in the so-called cellulose-cement bath on a forming drum, on which further layers are applied. Such a production method provides this composite board with a layered structure. At the interface between the layers, delamination may occur between the individual layers due to lack of adequate adhesion. This is one of the factors that reduce the durability of the material [4-6]. Additionally, it should be noted that the cement matrix, which is the main component of the material, or more precisely the calcium phases contained in it, reacts with carbon dioxide from the atmosphere. Although in the first years of exposure of boards to the environment, this phenomenon has a positive effect on interfacial connections, after several years the degree between layered bonds begins to decrease due to the effect of stresses caused by moisture and temperature [7-10]. Coal reactions with hydration products also have...
a negative impact on the condition of the material. They cause an increase in the moisture movement in the material structure, which leads to delamination in the material. This process is of course, spreading over time, but finally the strength of the element decreases almost twice after about 10 years of exposure to the environment. This fact calls into question the further suitability of fibre cement boards. Nowadays, material tests carried out on fibrous cement materials concerned the determination of standard physicochemical parameters in newly produced materials. Therefore, an accurate method is needed that would allow to assess the condition of the panels, especially elements that are long-term exposed to environmental conditions and high temperatures. It seems that acoustic emission method can be the right method for this.

2. Materials and methods

2.1. Materials

The research involved three series of fibrous cement materials marked with the letters PZBS, PZBMK and PZBMD. The tested samples were cut from a fibre cement board with dimensions of 3.1 x 1.25 m. The dimensions of the tested elements were 300x50x8 mm. Each series consisted of 5 samples. Samples marked with PZBS were in an air-dry state. The PZBMK designation indicates that the samples were subjected to impregnation in water for 1 h immediately before the test, while the PZBMD samples were soaked for 24 h.

| Properties                  | Values for samples from series PZBS/PZBMK/PZBMD |
|-----------------------------|--------------------------------------------------|
| Density [g/cm³]             | >1.6524                                          |
| Porosity [%]                | >18                                              |
| Thermal properties          | No danger of ignition or spread of fire           |
| Way of application          | Elevation: external wall cladding, balcony panels, railings, balustrades |

Three-point bending tests were carried out on a test bench using the Zwick-Roell testing machine at the Kielce University of Technology. The bending speed was 0.1 mm / min.

The acoustic emission tests (AE) during bending tests were carried out using the AMSY-5 type set. Two broadband sensors were used, which were clamped in the middle of the sample. A coupling resin layer was applied on the contact surface.

The view of the test stand for three-point bending tests and acquisition of AE signals is shown in Figure 1.

2.2. Methods

Acoustic emission is included in non-destructive methods mentioned in the PN-EN 473:2008 standard, and described and defined in PN-EN 1330-9:2009 and PN-EN 13554:2011. According to the definition, acoustic emission is a disappearing elastic wave, which is the result of a rapid release of energy accumulated in the material by propagating micro damage (increase of micro-gaps, movement of dislocation groups) in the material or through the process (friction, leaks, etc.). The frequency range typical for acoustic emission is usually determined in the range of 20 kHz-2 MHz.

The AE (Acoustic Emission) method is a passive non-destructive method. Its main advantages are:
- high sensitivity of the AE method;
- the ability to conduct tests without need to shutting down the equipment;
- possibility of conducting continuous tests;
• the ability to locate the source of AE signals generated by damage.

The stimulus that triggers the release of energy and the generation of elastic waves can be the effect of load, environment or temperature change. The processes accompanied by acoustic emission are both changes in the micro and macro scale, among others: cracks, plastic deformations, corrosion, leaks (leakages), structural and phase transformations, chemical reactions, delamination, cracking of fibers and matrix in composites, etc.

![Figure 1. View of the test bench.](image)

Acoustic waves propagate in all directions from the source, so one or more sensors mounted on the object or element can register them. During propagation, AE waves are suppressed, which limits the distance, at which they can be detected. This distance depends on many factors, first, on the material properties, the geometry of the object and the level of interference from the acoustic background. [13-15].

According to PN-EN 1330-9:2009, the AE signal can be characterized by the following parameters: amplitude, energy, rise time, number of transgression thresholds.

The basis of programs analysing Vallen's data is fast Fourier transform and wavelet transform. Wavelet transform means analysing the signal in different frequency bands, with different resolution, through its decomposition. This can be achieved by: signal approximation, emphasizing detailed information (e.g. discontinuities, sharp peaks), as well as decomposing (or recreating) finite, non-periodic or non-stationary signals. Thanks to these features, wavelet analysis can be used as a real method of signal processing in damage detection, e.g. for detecting a lone signal, signal-to-noise separation, frequency band analysis.

3. Results and discussions

During the tests of acoustic emission generated during the three-point bending test carried out on the test stand, a number of parameters were recorded, which then were analysed. These parameters include for example: maximum force, number of events, signal energy. The analysis of these quantities was carried out using the Vallen Visual AE program. These characteristics are shown in Tables 2-4.
Table 2. The characteristics of AE signals for each sample PZBS series

| Symbol of board | PZBS1 | PZBS2 | PZBS3 | PZBS4 | PZBS5 |
|-----------------|-------|-------|-------|-------|-------|
| Maximal load     | 0.261 | 0.261 | 0.267 | 0.274 | 0.258 |
| [kN]             |       |       |       |       |       |
| Total number of AE counts | 206    | 526    | 577    | 462    | 394    |
| Maximal energy of AE events | 679452 | 1094933 | 1260601 | 985412 | 1014256 |
| [eu]            |       |       |       |       |       |

Table 3. The characteristics of AE signals for each sample PZBMK series

| Symbol of board | PZBS1 | PZBS2 | PZBS3 | PZBS4 | PZBS5 |
|-----------------|-------|-------|-------|-------|-------|
| Maximal load     | 0.277 | 0.284 | 0.253 | 0.246 | 0.224 |
| [kN]             |       |       |       |       |       |
| Total number of AE counts | 293    | 234    | 150    | 326    | 179    |
| Maximal energy of AE events | 708348 | 31220  | 465464 | 547821 | 347852 |
| [eu]            |       |       |       |       |       |

Table 4. The characteristics of AE signals for each sample PZBMD series

| Symbol of board | PZBS1 | PZBS2 | PZBS3 | PZBS4 | PZBS5 |
|-----------------|-------|-------|-------|-------|-------|
| Maximal load     | 0.213 | 0.237 | 0.205 | 0.197 | 0.224 |
| [kN]             |       |       |       |       |       |
| Total number of AE counts | 64    | 65    | 643   | 85    | 112   |
| Maximal energy of AE events | 384632 | 652899 | 15640248 | 446172 | 597416 |
| [eu]            |       |       |       |       |       |

Exemplary graphs showing the number of events and the energy of signals as a function of time, recorded during tests are presented in Figures 2-4. A power gain curve was additionally applied to the signal energy graph.

![Exemplary graphs showing the number of events and the energy of signals as a function of time](image-url)

Figure 2. Graphs of registered AE descriptors for the exemplary sample from the PZBS series
a) counting of counts in a function of time b) graph of the energy dependence of signals in time with the force increment curve plotted.
Figure 3. Graphs of registered AE descriptors for the exemplary sample from the PZBMK series a) counting of counts in a function of time b) graph of the energy dependence of signals in time with the force increment curve plotted.

Figure 4. Graphs of registered AE descriptors for the exemplary sample from the PZBMD series a) counting of counts in a function of time b) graph of the energy dependence of signals in time with the force increment curve plotted.

Analysing tables 2-3 and Figures 2-4 one can observe a significant difference in the process of destroying the tested samples. In the case of dry samples and saturated in water for 1 h, no significant differences were observed in the distribution of registered AE descriptors as a function of time. The maximum breaking force values for individual samples of both series also do not differ significantly. A clear difference can be seen in the case of PZBMD series samples. Long soaking in water significantly affects both the nature of the number of AE counts and AE event energy as well as the force value. In the case of samples from all series, acoustic activity was recorded from the beginning of the analysed runs. Differences occur after reaching the maximum force value. In the samples from the PZBS and PZBMK series, the number of counts after reaching $F_{\text{max}}$ drops significantly. In the case of PZBMD series, it remains high until the test is completed. The comparison of the number of counts for samples indicates, however, that in the case of samples soaked in water for 24 hours, it is significantly lower, which was identified with the fact that the structure of the material softened, and thus the way of destroying the sample was less violent. It can be observed that in samples in the air-dry state, the AE counts recorded after reaching the maximum load level are not associated with a significant level of signal energy. A different situation occurs for samples of the PZBMK and PZBMD series.

Figures 5-7 show examples of the shapes of the signal generated when the sample was destroyed and their interpretation after the FTT (Fast Fourier Transform) analysis. Using the Vallen Wavelet module dedicated to the Vallen AMSY-5 software, the frequency spectrum signal diagrams for the sample PZBS sample (Fig. 5), PZBMK (Fig. 6) and the PZBMD series (Fig. 7) were determined at the time of destruction. Analysing the presented graphs, it can be observed that in the case of samples of the PZBS and PZBMK series, peak amplitudes occur for frequencies in the range of 30-500 kHz. In the entire analysed waveform, the signal is characterized by significant peaks in the field.
of amplitude. However, the values of the amplitudes achieved are not high. This spectrum was classified as induced by breaking the reinforcement. In the case of the PZBMD series, the signal runs more flat, which was identified as the softening of the material structure. A narrower frequency range of 30-40 kHz was also determined for the sample in this series.

Figure 5. Frequency spectrum of the sample signal of the PZBS series.

Figure 6. Frequency spectrum of the sample signal of the PZBMK series.

Figure 7. Frequency spectrum of the sample signal of the PZBMD series.

The evaluation of the AE signals of the tapes under study was also performed in the time-frequency domain, determining the two-dimensional spectrum of the spectral power density. Figures 8-10 show the spectrogram of the spectral power density of AE signals generated by the tested fibre cement board samples.

The presented spectrograms of the spectral power density show time-frequency structures differing in the bands of dominant frequencies. In the case of samples from the PZBS and PZBMK series, the band of dominant frequencies is in the range of 30-700 kHz (Figure 8, 9). For a sample from the PZBMD series, this band was determined in the range of 30-350 kHz (Figure 10). The largest amplitude values have frequency components in the range from 150 to 250 kHz for samples from the PZBS and PZBMK series (Figure 8, 9). For the PZBMD series sample the highest amplitude values were observed for frequency components from 75 kHz to 100 kHz (Figure 10). Based on the analysis of spectrograms determined for AE signals generated by samples from the PZBS and PZBMK series, significant differences in their time-frequency structure were found. A significant stratification of the acoustic structure of the analysed AE signal was observed, as well as a different distribution of individual frequency structures in time compared to the sample from the PZBMD series. This phenomenon
was also related to the fact that the structure of material subjected to long-term imbibition in water was softened.

**Figure 8.** Two-dimensional spectrogram of spectral density of EA signals generated during bending of cement-fibre board samples for the sample from the PZBS series.

**Figure 9.** Two-dimensional spectrogram of spectral density of EA signals generated during bending of cement-fibre board samples for the sample from the PZBMK series.
Figure 10. Two-dimensional spectrogram of spectral density of EA signals generated during bending of cement-fibre board samples for the sample from the PZBMD series.

4. Conclusions

Cellulose composites, due to the different nature of the components that make them, are more exposed than others to the defects, both at the stage of their production and during operation. These defects do not always lead to the destruction of the material and often products in which there are, for example, local cracks and/or delamination can be successfully exploited over many years. However, there is a danger of damage development or creating new ones in operating conditions, and consequently damaging the product. Monitoring material conditions in engineering structures allows avoiding such a phenomenon. Modern technology offers a number of new possibilities in this area, in particular using non-destructive testing methods.

It should be emphasized that when using NDE methods, it is essential to ensure the correct interpretation of the information obtained. This requires analysis of the behaviour of the monitored structure or material under the conditions of stress field and environment in the context of possible destruction processes.

The paper presents a proposal for the use of non-destructive acoustic emission method and time-frequency analysis for testing fibre cement boards. The tests were carried out on two series of samples cut from a fibre cement board available on the market. Obtained results of the research allowed observing changes occurring in the material under the influence of load. The method showed the applicability in the construction practice. Therefore, it should be further developed to diagnose fibrous cement materials.

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