WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2021.137155

ARCHIVES OF CIVIL ENGINEERING

Vol. LXVII ISSUE 2 2021

s. 67–83

Research paper

Impact of operating conditions on the strength and frequency of destruction of fibre-cement composites

A. Adamczak-Bugno[1], A. Krampikowska[2]

Abstract: The paper examines the impact of possible operational factors on strength and frequency parameters generated by bending of fibre-cement panels. The tests were performed on elements cut out of a standard commercially available panel. The samples were exposed to factors described as environmental (soaking in water, bath-drying cycles, freeze-thawing cycles) and unique (flame ignition and high temperature exposure) and then subjected to three-point bending tests. Acoustic emission (AE) signals were acquired during the external load application. After the measurements were completed, the strength of individual elements was determined and the frequencies generated during bending were calculated. The obtained results were analysed statistically. Comparing the results obtained for a group of samples subjected to environmental and unique factors, significant differences between them were noted. It was noted that the decrease in the strength of the samples is related to the emission of lower frequency sounds. It was found that the application of the presented methodology allows to determine the condition of the fibre-cement boards in use.

Keywords: fibre-cement composites, ventilated façades, acoustic emission method, bending strength

[1] MSc., Eng., Kielce University of Technology, Faculty of Civil Engineering and Architecture, Al. Tysiąclecia Państwa Polskiego 7, 25-314 Kielce, Poland, e-mail: aadamczak@tu.kielce.pl, ORCID: https://orcid.org/0000-0003-3314-3801
[2] PhD., Eng., Kielce University of Technology, Faculty of Civil Engineering and Architecture, Al. Tysiąclecia Państwa Polskiego 7, 25-314 Kielce, Poland, e-mail: akramp@tu.kielce.pl, ORCID: https://orcid.org/0000-0002-1784-9989

1. Introduction

Fibre-cement cladding panels are a material known in construction for years. Currently, it is experiencing a renaissance because it is safe for health and has extraordinary aesthetic qualities that give the building an original look [1-2].

In the 1970s and 1980s, asbestos, which proved to be a carcinogenic material, was used to produce fibre cement and steps were taken to eliminate the harmful component. Currently, fibre-cement cladding panels are made from Portland cement with the addition of synthetic cellulose fibres. Cement accounts for 90% of the production mixture and is responsible for the binding of the material and its final durability. Cellulose makes only 10% of fibre-cement cladding panels. It is gap filler and additive that provides the right amount of water in the cement setting process. It also increases the density of the final product. To improve the appearance and flexibility of fibre-cement panels, mineral substances are also added to them [3-5].

The mixture of these materials is layered in the production process and then pressed. The production technology allows obtaining highly-durable fibre-cement panels. The façade made in this system does not harm the environment, as the material is completely recycled [6-8].

Installation of the fibre-cement cladding panels does not require any wet work, which makes it possible to plan the works at any time of the year. Cladding panels are usually laid on the insulation layer, fixing them to the previously prepared system grid substrate. When installing the cladding on the façade, remember to move the panels away from the insulation layer, and to leave the vent holes. Fibre-cement panels on façades can be used for new buildings as well as for renovation of existing buildings [9-10].

Fibre-cement cladding elements used on façades are exposed to characteristic operating conditions (storing conditions). The panels are periodically soaked and dried and are exposed to the freeze-thawing process. Building façades are also exposed to UV radiation. Moreover, during the service life of fibre-reinforced cement elements, exceptional situations related to fire and high temperatures may occur. Therefore, it is considered appropriate to conduct tests on fibre-cement elements reflecting the indicated conditions[11-12].

The majority of studies on fibre-cement panels to date have been devoted to the impact of operational factors [13–15] and high temperatures, tested by examining the physicochemical parameters of the panels, mainly their bending strength (MOR). The article of Ardanuy et al [4] presents the results of tests, among others, on the impact of high temperature on fibre-cement panels, but only in relation to the bending strength MOR. Li et al. [16] studied the impact of high temperatures on the composites produced by extrusion but also solely on the basis of their mechanical properties. Non-destructive testing of fibre-cement panels was mainly limited to the detection of imperfections arising at the production stage. The works of Drelich et al [17] and Schabowicz and Gorzelańczyk [18] presented the possibility of using Lamb waves in a non-contact ultrasonic scanner to detect defects in fibre-cement panels at the production stage. The article [19] by Stark describes the method of delamination detection in composite using a moving ultrasonic probe. The works of Berkowski et al [20], Hoła and Schabowicz [21] and Davis et al. [22] the impact-echo method was proposed together with the impulse response method for delamination identification in fibre-cement elements. However, when analysing the results, it was found that due to the fact that the impulse response method is used to test elements thicker than 100 mm, it does not give unambiguous results in testing fibre-cement panels. Preliminary tests also proved that hitting the board with a hammer can cause damage, which is another reason why the impulse response method is not suitable for fibre-cement panels. Also, the impact-echo method is not recommended for testing standard fibre-cement panels as it has been reported that multiple reflections of waves cause interference, which makes the interpretation of the obtained image difficult [20]. It is therefore determined that this method is reliable for fibre-cement panels thicker than 8 mm.

There is little information in the literature on the use of other non-destructive testing methods for fibre-cement panels. Research described in Chady et al. [23] and Chady and Schabowicz [24] demonstrated that the terahertz method (T-Ray) is suitable for testing fibre-cement panels. The terahertz signals are very similar to ultrasonic signals, but their interpretation is more complicated. In the paper [25], the microtomography method was used to identify delamination and low-density areas in fibre-cement panels. The test results indicated that this method clearly reveals the differences in the microstructure of the panels and can therefore be a useful tool for testing the structure of fibre-cement panels, where defects may occur due to production errors. A disadvantage of the methodology may be that it can only be used for small elements. It should be noted that so far, few cases of testing fibre-cement panels by means of acoustic emission have been reported in the literature. Ranachowski, Schabowicz et al. conducted pilot studies on fibre-cement panels produced by extrusion, including those exposed to high temperature, in which the acoustic emission method was used to determine the impact of cellulose fibres on the panel strength and attempts were made to distinguish AE events emitted by fibres and matrix. The results of these tests confirmed the usefulness of this method for testing fibre-cement panels. The works [26] of Gorzelańczyk et al. proposed to use the acoustic emission method to investigate the impact of high temperature on fibre-cement panels. It should be mentioned that the impact of high temperatures on concrete and the interdependencies related to this type of impact have been extensively described using the acoustic emission method; example is work [27] by Ranachowski. Moreover, the acoustic emission method is successfully used in the testing low thickness materials, for example steel elements and polymer-based composites [28]. The indicated methodology is also used in the testing of food products with considerable tenderness [29].

It should remembered that, in addition to the effects of heat and fire, one of the most damaging factors for many construction products, in particular composite products containing reinforcement in the form of different fibres, especially organic fibres (such as cellulose fibres), is the effect of negative temperatures. Studies using acoustic emission were performed also in the works [30-33].

Therefore, the authors state that it is possible to link the frequency of generated acoustic emission signals with the strength parameters of fibre-cement panels.

2. Materials and methods

Testing on fibre cement panels was conducted for the elements exposed to environmental and unique factors for the following test cases:

- air-dry condition (no destruction, reference);
- soaking in water for 1 hour;
- soaking in water for 24 hour;
- 25 bath-drying cycles;
- 50 bath-drying cycles;
- 10 freeze-thaw cycles;
- 25 freeze-thaw cycles;
- 50 freeze-thaw cycles;
- 100 freeze-thaw cycles;
- direct exposure to flame (resulting in a temperature of up to 400°C) for 2.5 minutes;
- direct exposure to flame (resulting in a temperature of up to 400°C) for 5 minutes;
- direct exposure to flame (resulting in a temperature of up to 400°C) for 7.5 minutes;
- direct exposure to flame (resulting in a temperature of up to 400°C) for 10 minutes;
- the temperature of 230°C for 3 hours.

The first-case panels – reference, were stored in constant laboratory conditions (+23°C, 60% humidity).

Samples from 2-3 series were immersed in water at room temperature (approx. 23°C) for 1 hour and 24 hours respectively and then subjected to wet bend tests.

Bath-drying cycles (4-5 cases) were conducted by alternately immersing the samples in water at an ambient temperature higher than5°C (for approx. 23°C)18 hours and drying in a ventilated dryer at temperature 60°C (±5°C) and relative humidity less than 20% for 6 hours). The number of cycles depended on the test case.

Cyclic freeze-thawing (6-9 cases) was performed in an air-water environment by alternate cooling (freezing) in a freezer −20°C (±2°C) for 2 hours and keeping at this temperature for another hour and heating (thawing) in a water bath at this temperature 20°C (±2°C) for two hours and keeping at this temperature for another hour. During the cooling and heating (freezing and thawing) cycles, the samples were laid out in such a way as to ensure free circulation of the conductive medium (air in the freezer or bath water).

Fire is an exceptional factor characterised by a high temperature, occurring, among others, during a fire. The destruction of fibre-cement panels consisted in applying a flame of approx. 400°C for 2.5 to 10 minutes, tested at intervals of 2.5 minutes (10-13 cases).

Fibre-cement panels were burned out in the laboratory furnace at a temperature of 230°Cfor 3 hours at which the cellulose fibres are degraded. The choice of appropriate temperature and burn-up time was determined on the basis of the literature on the impact of temperatures on cellulose, as well as own preliminary and foreign studies, in order to achieve complete destruction of the fibres contained in the plates.

All test samples were cut out of a 310×125 cm factory panel. The dimensions of each tested element were 30×5×0.8 cm. The test samples were subjected to three-point bending tests. The settling velocity of the load mandrel was 0.1 mm/min. The axial distance between the support points was 20 cm and the radius of the supports and mandrel was 1 cm. Acoustic emission signals were acquired during each bending test. For this purpose, two sensors with built-in preamplifiers with 25-80 kHz and 100-450 kHz measuring ranges were mounted on the sample surface near the supports (Figure 1).

The tested fiber cement boards were produced using the Hatschek process. The basic mixture consisted of cement, sand, cellulose and water (autoclave drying). The raw material used for the production of air-dried fiber cement consists for the most part of a binder - Portland cement. In order to optimize the properties of this product, additional materials such as powdered lime are added to it. The production process of the panels follows the described cycle. After the materials are mixed together, a suspension forms. The liquid mixture is delivered to a vat containing rotating mesh rollers.

The rollers collect the solids by removing some of the water. The tape moving along the surface of the rolls collects a thin layer of fiber cement that forms on each of them. The accumulated layered plate is moved to vacuum drainage devices which remove most of the water. By means of the belt, the wet mass is transferred to the forming drum, on which subsequent layers are applied until the required thickness is achieved. After obtaining the appropriate thickness of the sheet, the built-in automatic cutting knife of the forming drum is turned on, and the raw board is placed on the conveyor and then placed on a stack. The stacked damp plates are separated by steel sheets. The stacked plates are then transferred to a press that exerts a pressure of at least 12.000 tons. As a result, the boards are compact and have a high density. Then the plates are dried.

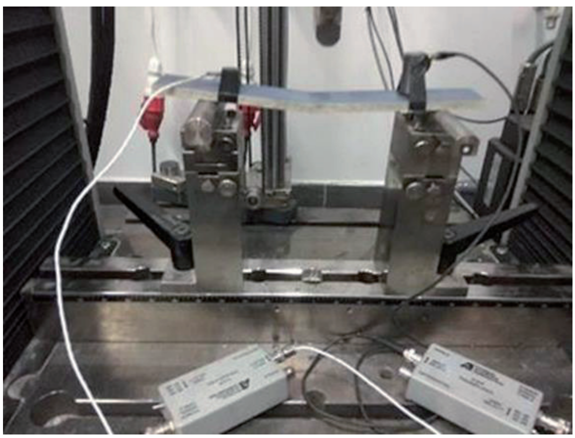

Fig. 1. View of the test bench.

After the tests, the bending strength of the samples and the average frequency values of AE signals generated during the tests were analysed. The bending stresses were determined according to the formula [34]:

$$\frac{3 \cdot F \cdot l}{2 \cdot b \cdot h^2}$$

F – load/force [N];

l – span in the axes of support [mm];

f – maximum deflection [mm];

b – sample width [mm];

h – sample thickness [mm];

a – the distance between the axis of support and the axis of load application [mm].

The average frequency values before the moment of destruction were recorded and read using processor and Vallen AE software.

The data obtained during the tests were analysed statistically and the impact of particular factors on the obtained results was determined.

3. Results and discussion

Table 1. Descriptive statistics

Parameter	Test case	N	Mean	Median	Min	Max	Standard deviation
Bending strength *MOR* [MPa]	1	10	25.034	24.380	23.440	28.130	1.5340
	2	10	25.033	24.845	23.440	27.190	1.2527
	3	10	25.033	24.845	23.440	27.190	1.2527
	4	10	24.283	24.380	22.500	26.250	1.1214
	5	10	15.375	15.000	14.060	17.810	1.1009
	6	10	24.939	24.845	23.440	26.250	0.9035
	7	10	21.470	21.560	19.690	23.440	1.1211
	8	10	21.469	21.560	20.630	22.500	0.6895
	9	10	21.095	21.095	19.690	22.500	0.7943
	10	10	9.003	9.380	7.500	10.310	0.79084
	11	10	9.697	10.045	8.440	10.310	0.7635
	12	10	4.689	4.690	3.750	6.560	0.8839
	13	10	3.656	3.750	2.810	4.690	0.6936
	14	10	1.718	1.785	1.410	1.880	0.1847

Average event frequency EA before reaching F_{max} [kHz]	1	10	572.800	566.500	492.000	673.000	53.2954
	2	10	539.500	546.500	459.000	624.000	55.4922
	3	10	555.500	563.000	424.000	681.000	77.0285
	4	10	517.700	520.000	473.000	569.000	33.6850
	5	10	418.000	418.500	316.000	517.000	62.0878
	6	10	519.500	512.500	425.000	621.000	65.7288
	7	10	485.300	492.000	379.000	592.000	65.8366
	8	10	448.300	427.000	376.000	552.000	61.0702
	9	10	385.700	376.500	291.000	505.000	72.5811
	10	10	280.400	289.000	151.000	384.000	62.4645
	11	10	210.100	214.000	174.000	245.000	21.8502
	12	10	195.800	189.000	96.000	321.000	59.7361
	13	10	167.000	161.500	119.000	237.000	36.8028
	14	10	142.200	140.000	87.000	203.000	39.8826

IBM SPSS Statistics 26 was used to analyse the data presented. The significance level was taken as 0.05. The Shapiro-Wilk test was chosen to test the standard distribution and the Levene test to test the homogeneity of variance. Due to the lack of standard distribution for some data and the lack of homogeneity of variance in most cases, a group of non-parametric tests for independent variables were used to compare mean distributions, in particular the test for many Kruskal-Wallis groups.

First, all data were pre-tested in order to select the appropriate test groups to examine the data. The groups examined are approximately equinumerous. Therefore, standard distributions of data in individual groups were studied with the Shapiro-Wilk test. For most data, there are no grounds to reject the hypothesis of standard distribution. The Levene test was then performed to examine the homogeneity of variance. In most groups there is no homogeneous variance. Therefore, in order to examine the distributions, it was decided to use the non-parametric test for Kruskal-Wallis independent variables.

Data distributions for bending strength MOR [MPa] differ statistically significantly in individual groups (T=131,185, p=0,000). In the next step, a post-hoc Bonferroni test was performed to see where there are significant differences.

- For sample 1 the results are significantly higher (significantly higher average) than for samples 5, 7, 8, 9, 10, 11, 12, 13, 14, and do not differ statistically significantly from the results for samples 2, 3, 4, 6.
- For sample 2 the results are significantly higher (significantly higher average) than for samples 5, 7, 8, 9, 10, 11, 12, 13, 14, and do not differ statistically significantly from the results for samples 1, 3, 4, 6.
- For sample 3 the results are significantly higher (significantly higher average) than for samples 5, 7, 8, 9, 10, 11, 12, 13, 14, and do not differ statistically significantly from the results for samples 1, 2, 4, 6.
- For sample 4 the results are significantly higher (significantly higher average) than for samples 5, 10, 11, 12, 13, 14, and do not differ statistically significantly from the results for samples 1, 2, 3, 6, 7, 8, 9.
- For sample 5 the results are significantly higher (significantly higher average) than for samples 13, 14, significantly lower (significantly lower average) than for samples 1, 2, 3, 4, 6 and do not differ statistically significantly from the results for samples 7, 8, 9, 10, 11, 12.
- For sample 6 the results are significantly higher (significantly higher average) than for samples 5, 7, 8, 9, 10, 11, 12, 13, 14, and do not differ statistically significantly from the results for samples 1, 2, 3, 4.
- For sample 7 the results are significantly higher (significantly higher average) than for samples 10, 12, 13, 14, 14 significantly lower (significantly lower average) than for samples 1, 2, 3, 6 and do not differ statistically significantly from the results for samples 4, 5, 8, 9, 11.
- For sample 8 the results are significantly higher (significantly higher average) than for samples 10, 12, 13, 14, significantly lower (significantly lower average) than for samples 10, 12, 13, 14 and do not differ statistically significantly from the results for samples 4, 5, 7, 9, 11.
- For sample 9 the results are significantly higher (significantly higher average) than for sample 12, 13, 14, significantly lower (significantly lower average) than for samples 1, 2, 3, 6, and do not differ statistically significantly from the results for samples 4, 5, 7, 8, 10, 11.
- For sample 10 the results are significantly lower (significantly lower average) than for samples 1, 2, 3, 4, 6, 7, 8, and do not differ statistically significantly from the results for samples 5, 9, 11, 12, 13, 14.

- For sample 11 the results are significantly lower (significantly lower average) than for samples 1, 2, 3, 4, 6, are significantly higher (significantly higher average) than for sample 14 and do not differ statistically significantly from the results for samples 5, 7, 8, 9, 10, 12, 13.
- For sample 12 the results are significantly lower (significantly lower average) than for samples 1, 2, 3, 4, 6, 7, 8, 9, and do not differ statistically significantly from the results for samples 5, 10, 11, 13, 14.
- For sample 13 the results are significantly lower (significantly lower average) than for samples 1, 2, 3, 4, 5, 6, 7, 8, 9, and do not differ statistically significantly from the results for samples 10, 11, 12, 14.
- For sample 14 the results are significantly lower (significantly lower average) than for samples 1, 2, 3, 4, 5, 6, 7, 8, 9, 11 and do not differ statistically significantly from the results for samples 10, 3, 12, 13.

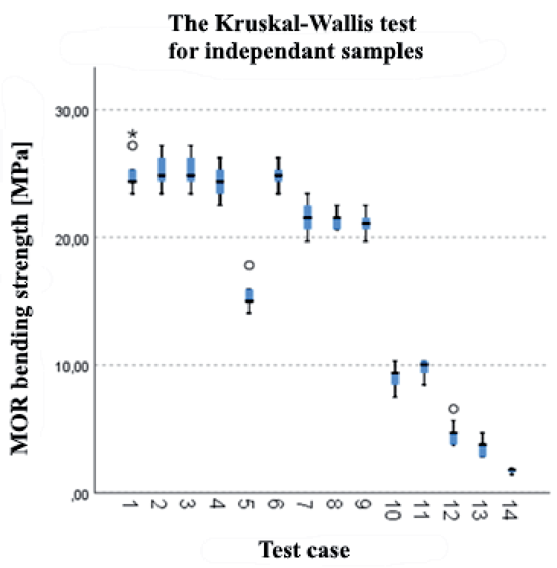

Fig. 2. Graphical representation of the results of the Kruskal-Wallis test for *MOR* bending strength.

Data distributions for the average frequency of EA events before reaching Fmax differ in individual groups in a statistically significant manner (T=116.902, p=0.000). In the next step, a post-hoc Bonferroni test was performed to see where there are significant differences.

- For sample 1 the results are significantly higher (significantly higher average) than for samples 5, 8, 9, 10, 11, 12, 13, 14, and do not differ statistically significantly from the results for samples 2, 3, 4, 6, 7.
- For sample 2 the results are significantly higher (significantly higher average) than for samples 5, 9, 10, 11, 12, 13, 14, and do not differ statistically significantly from the results for samples 1, 3, 4, 6, 7, 8.
- For sample 3 the results are significantly higher (significantly higher average) than for samples 5, 9, 10, 11, 12, 13, 14, and do not differ statistically significantly from the results for samples 1, 2, 4, 6, 7, 8.
- For sample 4 the results are significantly higher (significantly higher average) than for samples 9, 10, 11, 12, 13, 14, and do not differ statistically significantly from the results for samples 1, 2, 3, 5, 6, 7, 8.
- For sample 5 the results are significantly higher (significantly higher average) than for samples 11, 12, 13, 14, significantly lower (significantly lower average) than for samples 1, 2, 3 and do not differ statistically significantly from the results for samples 4, 6, 7, 8, 9, 10.
- For sample 6 the results are significantly higher (significantly higher average) than for samples 9, 10, 11, 12, 13, 14, and do not differ statistically significantly from the results for samples 1, 2, 3, 4, 5, 7, 8.
- For sample 7 the results are significantly higher (significantly higher average) than for samples 10, 11, 12, 13, 14, and do not differ statistically significantly from the results for samples 1, 2, 3, 4, 5, 6, 8, 9.
- For sample 8 the results are significantly higher (significantly higher average) than for samples 10, 11, 12, 13, 14, significantly lower (significantly lower average) than for samples, 3 and do not differ statistically significantly from the results for samples 2, 3, 4, 5, 6, 7, 9.
- For sample 9 the results are significantly higher (significantly higher average) than for sample 1, 2, 3, 4, 6, and do not differ statistically significantly from the results for samples 5, 7, 8, 10, 11.
- For sample 10 the results are significantly lower (significantly lower average) than for samples 1, 2, 3, 4, 6, 7, 8, and do not differ statistically significantly from the results for samples 5, 9, 11, 12, 13, 14.
- For sample 11 the results are significantly lower (significantly lower average) than for samples 1, 2, 3, 4, 5, 6, 7, 8 and do not differ statistically significantly from the results for samples 9, 10, 12, 13, 14.

- For sample 12 the results are significantly lower (significantly lower average) than for samples 1, 2, 3, 4, 5, 6, 7, 8, 9, and do not differ statistically significantly from the results for samples 10, 11, 13, 14.
- For sample 13 the results are significantly lower (significantly lower average) than for samples 1, 2, 3, 4, 5, 6, 7, 8, 9, and do not differ statistically significantly from the results for samples 10, 11, 12, 14.
- For sample 14 the results are significantly lower (significantly lower average) than for samples 1, 2, 3, 4, 5, 6, 7, 8, 9, and do not differ statistically significantly from the results for samples 10, 11, 12, 13.

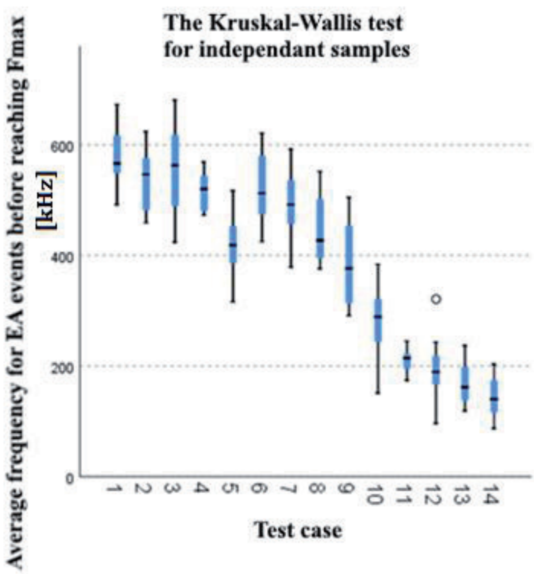

Fig. 3. Graphical representation of the Kruskal-Wallis test results for the average AE event frequency before reaching F_{max}.

4. Discussion

On the basis of the presented tests and the results obtained, it was found that some operating factors significantly affect both the value of bending strength and frequency of AE signals recorded before the moment of destruction. The greatest impact on the analysed parameters has bath-drying cycles, cyclic freeze-thawing, direct fire and high temperature effects. Chronic bathing and drying (5 series) reduces the frequency of recorded AE signals and the bending strength at 50 cycles by up to 30%. Passing through the value 0℃ (6-9 series) also causes a visible decrease in the frequency of the generated sounds and the bending strength values. The increase in the number of freeze-thaw cycles reduces the frequency of sounds and strength parameters by up to half. For the discussed test cases, the situation was associated with a reduction in the degree of binding between the fibres and the matrix caused by environmental factors. In turn, for samples from groups exposed to flame (10-13 series) and high temperature (14 series), the decrease in these parameters was even 80%. For these cases, the reduction of both parameters was associated with structure degradation and burn-up of reinforcement fibres.

5. Conclusion

The paper presents the results of three-point bending tests for fibre-cement elements subjected to environmental and unique factors with simultaneous acquisition of AE signals. The bending strength values and frequencies generated before the moment of destruction were analysed. Based on the results obtained, the following conclusions are drawn:

- The reduction of strength of fibre-cement elements is associated with the generation of lower bending frequencies for samples with unchanged mechanical parameters.
- The application of the acoustic emission method enables the tracking of frequencies associated with the formation of various types of changes in the material structure.
- The fibre-cement board structure destruction process is a complex mechanism, closely related to the presence of reinforcing fibres and the degree of bond between the reinforcement and the matrix.
- The frequencies generated by the changes in the fibre-cement structure are closely related to the presence of the fibre reinforcement and the degree of bond between the reinforcement and the matrix.
- The application of the acoustic emission method enables effective detection and monitoring of the initiation of changes in the structure affecting the reduction of mechanical parameters of the panels.
- The results obtained give the possibility to apply the AE method to assess the condition of full-sized fibre-cement elements.

References

[1] A. Akhavan, J. Catchmark, F. Rajabipour, “Ductility enhancement of autoclaved cellulose fibre reinforced cement boards manufactured using a laboratory method simulating the Hatschek process”, Constr. Build. Mater. 135: 251–259, 2017. https://doi.org/10.1016/j.conbuildmat.2017.01.001

[2] L. Fernández-Carrasco, J. Claramunt, M. Ardanuy, “Autoclaved cellulose fibre reinforced cement: effects of silica fume”, Constr. Build. Mater. 66: 138–145, 2014. https://doi.org/10.1016/j.conbuildmat.2014.05.050

[3] T. Horikoshi, A. Ogawa, T. Saito, H. Hoshiro, G. Fischer, V. Li, “Properties of polyvinyl alcohol fiber as reinforcing materials for cementitious composites”, Proceedings of the International RILEM Workshop on High Performance Fiber Reinforced Cementitious Composites in Structural Applications, 145–153, 2006.

[4] M. Ardanuy, J. Claramunt, R.D. Toledo Filho, “Cellulosic fibre reinforced cement-based composites: a review of recent research”, Constr. Build. Mater. 79: 115–128, 2015. https://doi.org/10.1016/j.conbuildmat.2015.01.035

[5] J. Liu, C. Li, J. Liu, G. Cui, Z. Yang, “Study on 3D spatial distribution of steel fibres in fibre reinforced cementitious composites through micro-CT technique”, Constr. Build. Mater. 48: 656–661, 2013.

[6] M. Jawaid, H. P. S. Abdul Khalil, “Cellulosic/synthetic fibre reinforced polymer hybrid composites: a review”, Carbohydr. Polym. 86: 1–18, 2011. https://doi.org/10.1016/j.carbpol.2011.04.043

[7] A. Adamczak-Bugno, G. Świt, A. Krampikowska, “Assessment of destruction processes in fiber-cement composites using the acoustic emission method and wavelet analysis”, IOP Conference Series-Earth and Environmental Science 214: 1-9, 2018. https://doi.org/10.1088/1757-899X/471/3/032042

[8] A. Adamczak-Bugno, G. Świt, A. Krampikowska, “Scanning electron microscopy in the tests of fibre-cement boards”, MATEC Web Conf. 174: 1–10, 2018. https://doi.org/10.1051/matecconf/201817402015

[9] M.E.A. Fidelis, F.A. Silva, R.D. Toledo Filho, “The influence of fiber treatment on the mechanical behavior of jute textile reinforced concrete”, Key. Eng. Mater. 600: 469–674, 2014. https://doi.org/10.4028/www.scientific.net/KEM.600.469

[10] V.D. Pizzol, L. M. Mendes, H. Savastano, M. Frías, F.J. Davila, M.A. Cincotto, V.M. John, G.H.D. Tonoli, “Mineralogical and microstructural changes promoted by accelerated carbonation and ageing cycles of hybrid fibre–cement composites”, Constr. Build. Mater. 68: 750–756, 2014. https://doi.org/10.1016/j.conbuildmat.2014.06.055

[11] A. Adamczak-Bugno, T. Gorzelańczyk, A. Krampikowska, M. Szymków, “Non-destructive testing of the structure of fibre-cement materials by means of a scanning electron microscope”, Badania Nieniszczące i Diagnostyka 3: 20–23, 2017. (In Polish)

[12] A. Adamczak-Bugno, A. Krampikowska, “The basics of a system for evaluation of fiber-cement materials based on acoustic emission and time-frequency analysis”, Mathematical Biosciences and Engineering 17(3): 2218-2235, 2020. https://doi.org/10.3934/mbe.2020118

[13] J. Claramunt, M. Ardanuy, J.A. García-Hortal, “Effect of drying and rewetting cycles on the structure and physicochemical characteristics of softwood fibres for reinforcement of cementitious composites”, Carbohydr. Polym. 79: 200–205, 2010. https://doi.org/10.1016/j.carbpol.2009.07.057

[14] B.J. Mohr, H. Nanko, K.E. Kurtis, “Durability of kraft pulp fibre-cement composites to wet/dry cycling”, Cem. Concr. Compos. 27: 435–448, 2005. https://doi.org/10.1016/j.cemconcomp.2004.07.006

[15] V.D. Pizzol, L.M. Mendes, H. Savastano, M. Frías, F.J. Davila, M.A. Cincotto, V.M. John, G.H.D. Tonoli, “Mineralogical and microstructural changes promoted by accelerated carbonation and ageing cycles of hybrid fibre–cement composites”, Constr. Build. Mater. 68: 750–756, 2014. https://doi.org/10.1016/j.conbuildmat.2014.06.055

[16] Z. Li, X. Zhou, S. Bin, “Fibre-Cement extrudateswith perlite subjected to high temperatures”, J.Mater. Civ. Eng.3: 221–229, 2004.

[17] R. Drelich, T. Gorzelańczyk, M. Pakuła, K. Schabowicz, “Automated control of cellulose fibre cement boards with a non-contact ultrasound scanner”, Autom. Constr. 57: 55–63, 2015. https://doi.org/10.1016/j.autcon.2015.04.017

[18] K. Schabowicz, T. Gorzelańczyk, “A non-destructive methodology for the testing of fibre cement boards by means of a non-contact ultrasound scanner”, Constr. Build. Mater. 102: 200–207, 2016. https://doi.org/10.1016/j.conbuildmat.2015.10.170

[19] W. Stark, “Non-destructive evaluation (NDE) of composites: Using ultrasound to monitor the curing of composites”, In Non-Destructive Evaluation (NDE) of PolymerMatrix Composites. Techniques and Applications, 1st ed. https://doi.org/10.1533/9780857093554.1.136

[20] P. Berkowski, G. Dmochowski, J. Grosel, K. Schabowicz, Z. Wójcicki, “Analysis of failure conditions for a dynamically loaded composite floor system of an industrial building”, J. Civ. Eng. Manag. 19: 529–541, 2013. https://doi.org/10.3846/13923730.2013.779319

[21] J. Hoła, K. Schabowicz, "State-of-the-art non-destructive methods for diagnostic testing of building structures—Anticipated development trends", Arch. Civ. Mech. Eng. 10: 5–18, 2010. https://doi.org/10.1016/S1644-9665(12)60133-2
[22] A. Davis, B. Hertlein, K. Lim, K. Michols, "Impact-echo and impulse response stress wave methods: Advantages and limitations for the evaluation of highway pavement concrete overlays", In Proceedings of the Conference on Nondestructive Evaluation of Bridges and Highways, Scottsdale, AZ, USA, 88–96, 1996.
[23] T. Chady, K. Schabowicz, M. Szymków, "Automated multisource electromagnetic inspection of fibre-cement boards", Autom. Constr. 94: 383–394, 2018. https://doi.org/10.1016/j.autcon.2018.07.018
[24] T. Chady, K. Schabowicz, "Non-destructive testing of fibre-cement boards, using terahertz spectroscopy in time domain", Badania Nieniszczące i Diagnostyka 1–2: 62–66, 2016. (In Polish)
[25] K. Schabowicz, Z. Ranachowski, D. Józwiak-Niedźwiedzka, Ł. Radzik, S. Kudela, T. Dvorak, "Application of X-ray microtomography to quality assessment of fibre cement boards", Constr. Build. Mater. 110: 182–188, 2016. https://doi.org/10.1016/j.conbuildmat.2016.02.035
[26] T. Gorzelańczyk, K. Schabowicz, M. Szymków, "Non-destructive testing of fibre-cement boards, using acoustic emission", Przegląd Spawalnictwa 88: 35–38, 2016. (In Polish)
[27] Z. Ranachowski, D. Józwiak-Niedźwiedzka, A. M. Brandt, T. Dębowski, "Application of acoustic emissionmethod to determine critical stress in fibre reinforced mortar beams", Arch. Acoust. 37: 261–268, 2012. https://doi.org/10.2478/v10168-012-0034-3
[28] M. Jawaid, H.P.S.A. Khalil, "Cellulosic/synthetic fibre reinforced polymer hybrid composites: A review", Carbohydr. Polym. 86: 1–18, 2011. https://doi.org/10.1016/j.carbpol.2011.04.043
[29] A. Marzec, P. Lewicki, Z. Ranachowski, T. Debowski, "The influence of moisture content on spectral characteristic of acoustic signals emitted by flat bread samples", In Proceedings of the AMAS Course on Nondestructive Testing of Materials and Structures, Centre of Excellence for Advanced Materials and Structures 127–135, 2002.
[30] B. Goszczyńska, G. Świt, W. Trąmpczyński, "Application of the IADP acoustic emission method to automatic control of traffic on reinforced concrete bridges to ensure their safe operation", Arch. Civ. Mech. Eng. 16: 867–875, 2016. https://doi.org/10.1016/j.acme.2016.06.003
[31] B. Goszczyńska, G. Świt, W. Trąmpczyński, "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", Bull. Polish Acad. Sci.: Tech. Sci. 63: 55–65, 2015. https://doi.org/10.1515/bpasts-2015-0007
[32] B. Goszczyńska, "Analysis of the process of crack initiation and evolution in concrete with acoustic emission testing", Arch. Civ. Mech. Eng. 2: 134–143, 2014. https://doi.org/10.1016/j.acme.2013.06.002
[33] A. Krampikowska, R. Pała, I. Dzioba, G. Świt, "The Use of the Acoustic Emission Method to Identify Crack Growth in 40CrMo Steel", Materials 12: 2140-2154, 2019. https://doi.org/10.3390/ma12132140
[34] 34. PN EN 12467 FIBRE-CEMENT FLAT SHEETS - PRODUCT SPECIFICATION AND TEST METHODS

Wpływ warunków eksploatacyjnych na wytrzymałość i częstotliwości niszczenia kompozytów cementowo-włóknistych

Słowa kluczowe*: kompozyty cementowo-włókniste, elewacje wentylowane, metoda emisji akustycznej, wytrzymałość na zginanie*

Streszczenie: Badania płyt włóknisto-cementowych przeprowadzono dla elementów podanych działaniu czynników eksploatacyjnych o charakterze środowiskowym i wyjątkowym dla następujących przypadków badawczych:

- stanu powietrzno-suchego (brak destrukcji, stan odniesienia, referencyjny);
- nasączania w wodzie przez 1 godzinę;
- nasączania w wodzie przez 24 godziny;
- 25 cykli kąpieli-suszenia;
- 50 cykli kąpieli-suszenia;
- 10 cykli zamrażania-rozmrażania;
- 25 cykli zamrażania-rozmrażania;

- 50 cykli zamrażania-rozmrażania;
- 100 cykli zamrażania-rozmrażania;
- bezpośredniego oddziaływania płomienia ognia (powodującego powstanie temperatury o wartości do 400°C) przez 2,5 minuty;
- bezpośredniego oddziaływania płomienia ognia (powodującego powstanie temperatury o wartości do 400°C) przez 5 minut;
- bezpośredniego oddziaływania płomienia ognia (powodującego powstanie temperatury o wartości do 400°C) przez 7,5 minuty;
- bezpośredniego oddziaływania płomienia ognia (powodującego powstanie temperatury o wartości do 400°C) przez 10 minut;
- oddziaływania temperatury 230°C przez 3 godziny.

Do analizy przedstawionych danych użyto programu IBM SPSS Statistics 26. Jako poziom istotności przyjęta została wartość 0,05.W celu zbadania normalności rozkładów wybrano test Shapiro-Wilka, a do zbadania homogeniczności wariancji test Levene'a. W związku z brakiem rozkładu normalnego dla niektórych danych oraz z brakiem homogeniczności wariancji w większości przypadków, do porównywania między sobą rozkładów średnich użyto grupy testów nieparametrycznych dla zmiennych niezależnych, w szczególności testu dla wielu grup Kruskala-Wallisa.

W pierwszej kolejności na wszystkich danych przeprowadzono wstępne testy, aby wybrać odpowiednie grupy testów do przebadania danych. Badane grupy są w przybliżeniu równoliczne. Zbadano zatem rozkłady normalne danych w poszczególnych grupach testem Shapiro-Wilka. Dla większości danych nie ma podstaw do odrzucenia hipotezy o rozkładzie normalnym, jednak zachodzą przypadki, w których dane nie mają rozkładu normalnego. Następnie przeprowadzono test Levene'a w celu zbadania homogeniczności wariancji. W większości grup brak homogenicznej wariancji. W związku z tym, w celu zbadania rozkładów, podjęta została decyzja o użyciu testu nieparametrycznego dla zmiennych niezależnych Kruskala-Wallisa.

Rozkłady danych dla wytrzymałości na zginanie MOR [MPa] różnią się w poszczególnych grupach w sposób statystycznie istotny (T=131,185, p=0,000). W następnym kroku przeprowadzono test post-hoc Bonferroniego w celu sprawdzenia, w których przypadkach zachodzą istotne różnice.

Na podstawie przedstawionych badań i otrzymanych rezultatów stwierdzono, że niektóre czynniki eksploatacyjne w sposób znaczący wpływają zarówno na wartość wytrzymałości na zginanie, jak i częstotliwości sygnałów AE rejestrowanych przed momentem zniszczenia. Największy wpływ na analizowane parametry mają cykle kąpieli-suszenia, cykliczne zamrażanie-rozmrażanie, bezpośrednie działanie ognia oraz wysoka temperatura. Chroniczne poddawanie elementów kąpieli i suszeniu (seria 5) powoduje obniżenie częstotliwości rejestrowanych sygnałów AE oraz wytrzymałości na zginanie przy 50 cyklach nawet o około 30%. Przejście przez wartość 0°C (serie 6-9) również powoduje widoczne obniżenie częstotliwości generowanych dźwięków oraz wartości wytrzymałości na zginanie. Przyrost liczby cykli zamrażania-rozmrażania wpływa na zmniejszenie częstotliwości dźwięków oraz parametrów wytrzymałościowych nawet o połowę. Dla omawianych przypadków badawczych zaistniałą sytuację powiązano ze zmniejszeniem stopnia wiązania pomiędzy włóknami a matrycą wywołanym oddziaływaniem czynników środowiskowych. Z kolei dla próbek z grup poddawanych działaniu płomienia ognia (serie 10-13) oraz wysokiej temperatury (seria 14) spadek omawianych parametrów wyniósł nawet 80%. Dla tych przypadków obniżenie obu parametrów powiązano z degradacją struktury oraz wypaleniem włókien zbrojących.

W artykule przedstawiono wyniki testów trzypunktowego zginania dla elementów włóknisto- cementowych poddanych działaniu czynników środowiskowych i wyjątkowych z jednoczesną akwizycją sygnałów AE. Analizie poddano wartości wytrzymałości na zginanie oraz częstotliwości generowanych przed momentem zniszczenia. Na podstawie otrzymanych wyników wyciągnięto następujące wnioski:

- Obniżenie wytrzymałości elementów włóknisto-cementowych wiąże się z generowaniem niższych częstotliwości przy zginaniu w odniesieniu do próbek o niezmienionych parametrach mechanicznych.
- Zastosowanie metody emisji akustycznej umożliwia śledzenie częstotliwości powiązanych z powstawaniem różnego rodzaju zmian w strukturze materiału.
- Przebieg procesu niszczenia struktury płyty cementowo-włóknistej jest mechanizmem złożonym i powiązanym w sposób ścisły z obecnością włókien zbrojących oraz stopniem wiązania pomiędzy zbrojeniem a matrycą.
- Częstotliwości generowane przez zmiany zachodzące w strukturze włókno-cementu są ściśle powiązane z obecnością zbrojenia w postaci włókien oraz stopniem wiązania między zbrojeniem a matrycą.
- Zastosowanie techniki emisji akustycznej umożliwia skuteczne wykrywanie i monitorowanie inicjacji zmian w strukturze wpływających na obniżenie parametrów mechanicznych płyt.
- Otrzymane rezultaty dają możliwość zastosowania metody AE do oceny stanu pełnowymiarowych elementach cementowo-włóknistych.

Received: 11.08.2020, Revised: 03.01.2020