Advances in Science and Technology Research Journal

Advances in Science and Technology Research Journal, 2025, 19(9), 65–79
https://doi.org/10.12913/22998624/205793
ISSN 2299-8624, License CC-BY 4.0

Received: 2025.04.09
Accepted: 2025.07.15
Published: 2025.08.01

Analysis of the influence of the distribution of recyclate rubber layers in the sandwich composite on the identification of damage initiation stress of composite materials using the acoustic emission method

Norbert Abramczyk[1], Katarzyna Panasiuk[1*], Krzysztof Dudzik[2], Daria Żuk[1]

[1] Department of Engineering Sciences, Faculty of Marine Engineering, Gdynia Maritime University, ul. Morska 81-87, 81-225 Gdynia, Poland
[2] Department of Marine Maintenance, Faculty of Marine Engineering, Gdynia Maritime University, ul. Morska 81-87, 81-225 Gdynia, Poland
* Corresponding author's e-mail: k.panasiuk@wm.umg.edu.pl

ABSTRACT

Annually, 1.5 billion tires—composed of up to 90% vulcanized rubber—are discarded worldwide. Due to its complex and cross-linked structure, vulcanized rubber is extremely difficult to recycle and reprocess. This study investigates the potential application of recycled rubber as a core material in sandwich composite structures. Given the potential use of these materials as structural elements, it is crucial to determine their operating stress limits. While design approaches in composite engineering typically rely on theoretical models and safety factors, the integration of additional testing methods enables more accurate insight into material degradation processes. Static tensile tests showed that the composite without rubber had a strength of approximately 120 MPa, whereas with the addition of 5% recycled rubber, a strength of approximately 100 MPa was achieved. Static tensile testing, conducted alongside acoustic emission (AE) monitoring, allows for identifying stress thresholds that correlate with increases in AE event counts, root mean square (RMS) values, or signal amplitude—parameters that signal structural changes within the composite during loading. The aim of this study was to establish allowable stress values for recycled rubber-based composites, considering different configurations of the rubber layer distribution using the AE method. Based on the read average values of the stresses at which damage is initiated in the composite materials, it is noticeable that despite the earlier values indicating better parameters of the K1 composite – 1 layer of rubber recyclate (64.8 MPa), comparable results are also obtained for the K3 – 3 layers of rubber recyclate (64 MPa) composite. Of the three tested materials, the K2 composite consisting of 2 layers of recyclate rubber is characterized by the lowest value (62.6 MPa).

Keywords: recyclate rubber, sandwich composites, static tensile test, acoustic emission, destruction process.

INTRODUCTION

Plastics and rubbers are widely used materials in the production of various products across numerous industries – not only in the automotive sector, but also in construction, packaging, toys, and more. Rubber is an elastomeric material characterized by its ability to undergo reversible deformations ranging from 100% to even 1000%, owing to its chemical structure and molecular weight. A low glass transition temperature (Tg) enables macromolecular chains to move and rotate around chemical bonds even at relatively low temperatures. Increasing irregularities in polymer chains or the presence of large substituents – such as in styrene-butadiene rubber (SBR) – leads to a higher glass transition temperature. The development of efficient vulcanization processes has significantly boosted the production of high-quality rubber at relatively low cost. Vulcanization is an irreversible cross-linking reaction in which curing agents (such as sulfur or peroxides) form a three-dimensional network between rubber macromolecules. The chemical and physical properties of cross-linked rubber are primarily influenced by parameters such as curing time, processing temperature, and the presence of fillers. When curing agents are introduced into unsaturated rubber, they enhance its durability by forming a cross-linked structure. As a result, vulcanized rubber becomes a thermosetting material – flexible, insoluble, and infusible – which cannot be reprocessed. From a recycling perspective, this represents a significant disadvantage once the material reaches the end of its service life [1–4].

Tires, as one of the primary products of the rubber industry, are complex composite materials designed to perform under a wide range of environmental conditions. Rubber serves as the main component in tire manufacturing, typically in the form of natural rubber (NR), SBR, nitrile butadiene rubber (NBR), or ethylene-propylene-diene monomer rubber (EPDM). However, the formulation of tires also includes reinforcing fillers, antioxidants, antiozonants, and preservatives, which collectively enhance their resistance to biodegradation, photochemical decomposition, and high temperatures [3, 5]. As a result, the disposal and recycling of used tires present a significant challenge – especially in light of the global expansion of the tire industry [1].

It is well known that the degradation of polymers, including biodegradation, is a slow process that poses significant environmental risks. As a result, the disposal of polymer-based waste has become a serious environmental concern. Tires, which consist of nearly 50% rubber, are among the most common polymer products. In 2017, global rubber production reached approximately 26.7 million tons, including 12.31 million tons of NR and 14.46 million tons of synthetic rubber [6]. Rubber waste can come from a variety of sources, such as discarded rubber pipes, belts, and footwear. However, the tire industry – accounting for about 65% of global rubber consumption – is the primary contributor to rubber waste. Consequently, rubber recycling is often synonymous with tire recycling. Currently, around 1.5 billion tires are disposed of worldwide each year. These tires contain up to 50% vulcanized rubber, which, due to its complex cross-linked structure, is difficult to recycle or reprocess using conventional methods [6].

Numerous studies have explored the recycling of used tires for energy recovery [7, 8] and through pyrolysis processes [9]. In recent years, several environmentally friendly recycling techniques have been developed, including triboelectric separation, froth flotation, and laser-induced breakdown spectroscopy. Despite their potential, these methods tend to be costly, and the properties of the recovered rubber – such as purity, particle size, shape, and surface morphology – can vary significantly [10–12]. Although vulcanized rubber waste presents substantial challenges for recycling due to its cross-linked structure, it remains a highly durable, strong, and flexible material. These characteristics make it a suitable candidate for use as a filler in the production of composite materials [6]. A growing body of literature is dedicated to the recycling and reuse of rubber recyclates. For instance, reference [13] reviews various approaches to rubber waste management, including thermal, mechanical, physical, chemical, and biological methods. The study outlines the advantages, limitations, and key challenges associated with each technique, while also evaluating the potential for implementing a circular economy in the rubber sector both now and in the future. Recent research also emphasizes the complex chemical composition of vulcanized elastomeric particles commonly used in playgrounds and sports surfaces. Notably, it introduces new data on the presence of trace elements and organophosphate esters in used tires and EPDM crumb rubber [14].

Mechanical strength tests of composites containing recycled rubber have been previously conducted [15–18]. Given the intention to use these materials in structural applications, it is essential to determine the allowable stress values, which serve as key performance parameters. However, in composite materials, these values are often difficult to define precisely, and design practices typically rely on theoretical models and safety factors. Therefore, it becomes necessary to employ complementary research methods that provide insight into the failure mechanisms of such materials. Previous studies [19–21] have shown that conducting static tensile tests in conjunction with acoustic emission (AE) monitoring makes it possible to identify specific stress levels at which increases in parameters such as the number of AE events, RMS values, or amplitude occur. These characteristic points are associated with structural changes in the composite during loading.

The objective of the present study was to determine the permissible stress values for composites incorporating recycled rubber, with particular consideration of the internal structure—specifically, the layering of the rubber-based core. The acoustic emission method was employed as a diagnostic tool to support this analysis.

METHODOLOGY

The study utilized a proprietary technology for the fabrication of composites based on glass fibres and epoxy resin, incorporating recycled rubber as an additive. All tested samples were produced using EM 1002/300/125 glass mat with randomly oriented fibres [22]. This mat, composed of E-glass fibres with low alkali content (< 1%), is well-suited for manual lamination processes, offering favorable mechanical properties and high resistance to environmental conditions. Due to these characteristics, the material is commonly used in various industries, including shipbuilding (e.g., boats, kayaks, yachts), transportation (e.g., automotive components, trailers, containers), and construction (e.g., wall panels, bus shelter structures).

The Epidian®6 epoxy resin with Z-1 hardener was used to produce the composites. Epidian®6 is used, among others, for the production of composites, chemically resistant coatings, fiber-reinforced pipes and adhesives. It is cured at room temperature with polyamides and amines, and at higher temperatures with other hardeners, e.g. acid anhydrides. 13 g of Z-1 hardener (aliphatic amine) was added per 100 g of resin. To modify the composites, Orzeł-Base rubber recyclate [23] from car tires with grains of 0.5–3 mm was used. After preliminary screening, the 0.5–1.5 mm fraction was selected as an additive to the composite matrix [23]. The chemical composition of the recyclate is consistent with the composition of the tire tread.

The reinforcement to matrix ratio of 40/60 (weight ratio), 12 layers of glass mat were used. Composites with the addition of rubber recyclate were designated as K1, K2 and K3 (constant content of recyclate 5%, different distribution between layers). The strength values were referred to the K0 composite. The recyclate distribution scheme is shown in Figure 1, and the composition details are in Table 1.

Each material variant was produced by hand lamination using brushes, rollers and moulds of dimensions 300 × 900 mm. The composites were pressed with a steel sheet (295 × 895 × 6 mm) with a pressure force of 675 N onto the mould to avoid resin leakage. The flow chart of the materials production is shown in Figure 2. The materials contained glass mat, rubber recyclate and Epidian®6 resin. The comparative composite K0 did not contain recyclate. The same amount of saturant, pressure, curing time (7 days) and temperature (22 °C) were used in all variants.

In order to perform static tensile tests on the manufactured composite material, specimens were prepared in accordance with the PN-EN

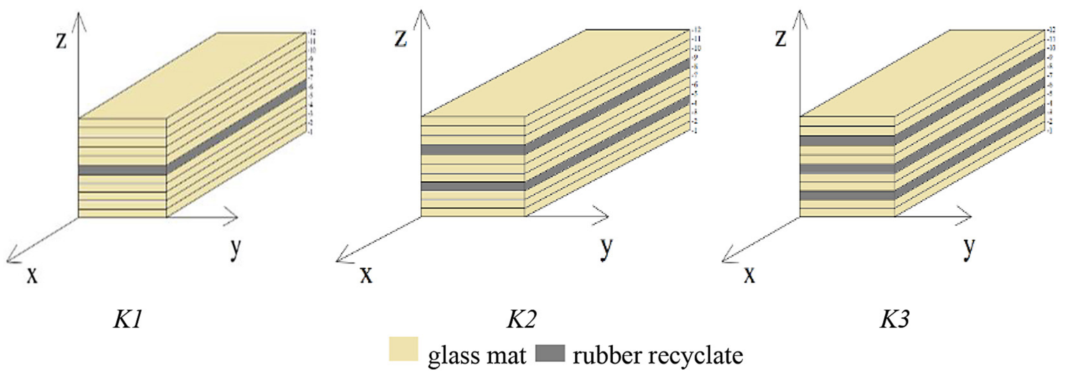


Figure 1. Schematic diagram of the arrangement of the recycled rubber layers in the produced composites [24]

Table 1. Characteristics and description of the composition of research materials [24]

Type of the composite	Method of distributing the recyclate	Number of layers of glass mat	Resin [%]	Rubber recyclate [%]
K0	none	12	60%	0%
K1	1 layer	12	60%	5%
K2	2 layers	12	60%	5%
K3	3 layers	12	60%	5%

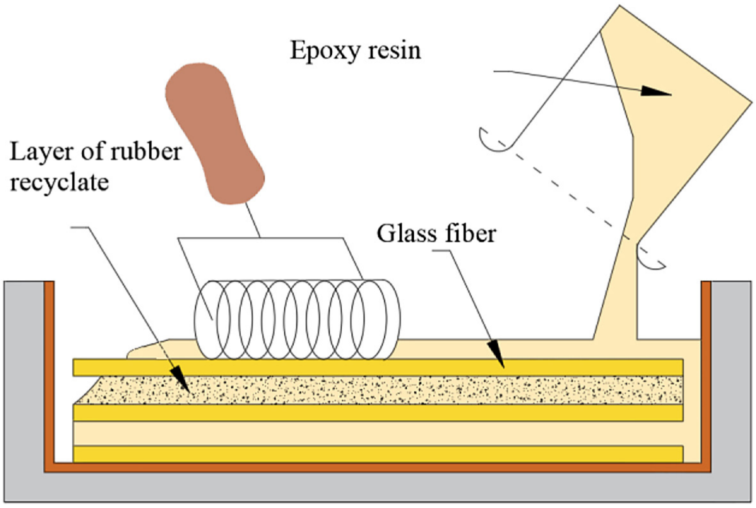


Figure 2. Scheme of the process of manufacturing the K1, K2, and K3 variants – the addition of rubber recyclate in the form of a sandwich layer [24]

ISO 527-4_2000P standard [25]. The tests were conducted in full compliance with this standard. Composite panel samples were cut using a water-jet cutting method, ensuring uniform dimensions and high precision across all specimens.

The mechanical testing was carried out using a Zwick&Roell MPMD P10B universal hydraulic testing machine, equipped with TestXpert II software for data acquisition and control. To measure specimen elongation during the tests, an Epsilon 3542 extensometer was employed. For selected specimens, tensile tests were supplemented with AE monitoring using a system provided by Physical Acoustics Company (PAC). A schematic diagram of the test setup is shown in Figure 3 [26].

As part of the AE testing, a specialized measurement setup was used, with the core component being a single-channel USB AE Node recorder, type 1283, operating within a frequency range of 20 kHz to 1 MHz. Signals from the sensor were amplified using a preamplifier with a bandwidth of 75 kHz to 1.1 MHz, enabling effective detection of diverse AE phenomena occurring in the composite material during tensile testing.

Signal detection was performed using an AE sensor of the VS 150M type, which operates within a frequency range of 100 to 450 kHz. This makes it well-suited for monitoring damage in layered composite materials. Data acquisition and analysis were conducted using AE Win for USB software, version E5.30, installed on the control computer. The software allowed real-time monitoring of AE parameters such as the number of recorded events, RMS signal level, amplitude, and individual signal energy.

All measurements were carried out in accordance with the applicable standards for acoustic emission testing [27–29], ensuring the reliability

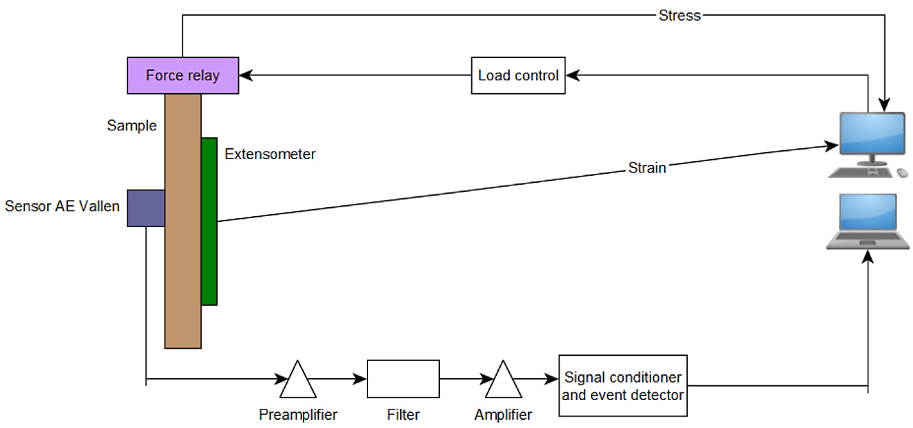


Figure 3. Diagram of the measuring station [26]

and comparability of the obtained results. Prior to testing, the specimen surface was properly prepared – cleaned and degreased – to ensure optimal contact between the AE sensor and the tested material. A coupling gel was applied between the sensor and the specimen surface to minimize acoustic wave transmission resistance and eliminate potential measurement disturbances. The sensor was secured to the specimen using an elastic tape, providing stable positioning throughout the duration of the test. This methodology enabled real-time recording of acoustic emission signals during mechanical loading of the specimen. As a result, it was possible to identify characteristic load thresholds corresponding to the initiation of first damage in composite structure.

TEST RESULTS

The results obtained during the tests, such as the effective value of the AE source signal (AE RMS), amplitude and the number of events for the material without recyclate and with recyclate in different locations, were correlated for comparison. The first of the analyzed parameters is the number of events (AE hits). It provides information on the number of exceedances of the AE signal amplitude in relation to the set discrimination threshold, and the causes of which are damages occurring in it, such as: cracking of the matrix and fibers inside the sample, delamination due to the addition of recyclate (among others), cracking at the fiber and matrix boundary. The Figure 4 presents a summary of the results obtained for selected samples from each type of tested materials for the number of events parameter (HITS) plotted on the stress-strain diagrams.

Based on the graphs for the number of events, their significant increase is visible after adding recyclate. During the stretching of the sample, even at low stresses, the matrix initially cracks together with the recyclate, and the rubber recyclate is thus displaced, which is also treated as subsequent events. A decrease in the stress values indicated by the first increase in the number of events (< 40) is visible. Analyzing the effect of the distribution of layers, it is noticeable that the most favorable in terms of the distribution of the number of events is the composite with 1 layer of rubber recyclate (K1), while the least favorable is the K2 composite with two layers, distributed symmetrically. The characteristics of the number of events, despite the addition of recyclate, do not differ significantly in the case of the K1 and K2 composites, which seems to be favorable in terms of designing structures from these materials. The

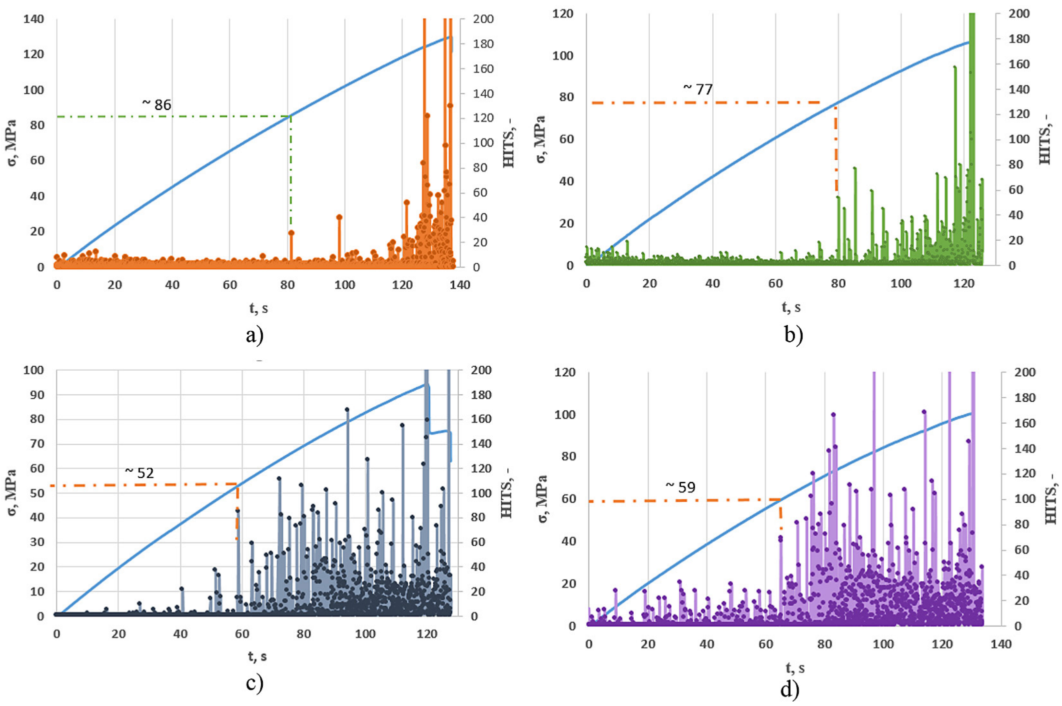


Figure 4. Graph of stress and number of AE hits, as a function of time for a selected specimens: (a) K0 – without recyclate, (b) K1, (c) K2, d) K3

next parameter that will be subject to evaluation will be the amplitude (Figure 5).

The Figure 6 shows an example graph for sample K0 illustrating the change in signal amplitude and frequency as a function of time.

Visible sudden increase in amplitude in the final phase of the test – sample rupture. A very high frequency signal (above 500 kHz) was not considered. Despite this, however, there is a noticeable increase in signal amplitude at these high frequencies for about 80 s of the test, which confirms the beginning of the destruction process considered in the RMS analysis. At the same time, the first changes occurred in the material generating a signal with a frequency of about 270–300 kHz (invisible in this view of the graph – visible in the graphs after the FFT analysis – Figure 8d).

Analyzing the obtained results from the amplitude, it is possible to read unambiguous parameters for the sample without the addition of recyclate and with one of its layers. In the case of composites with recyclate in the number of 2 and 3 layers, unfortunately, the results are not so obvious to read, there are increases in amplitude,

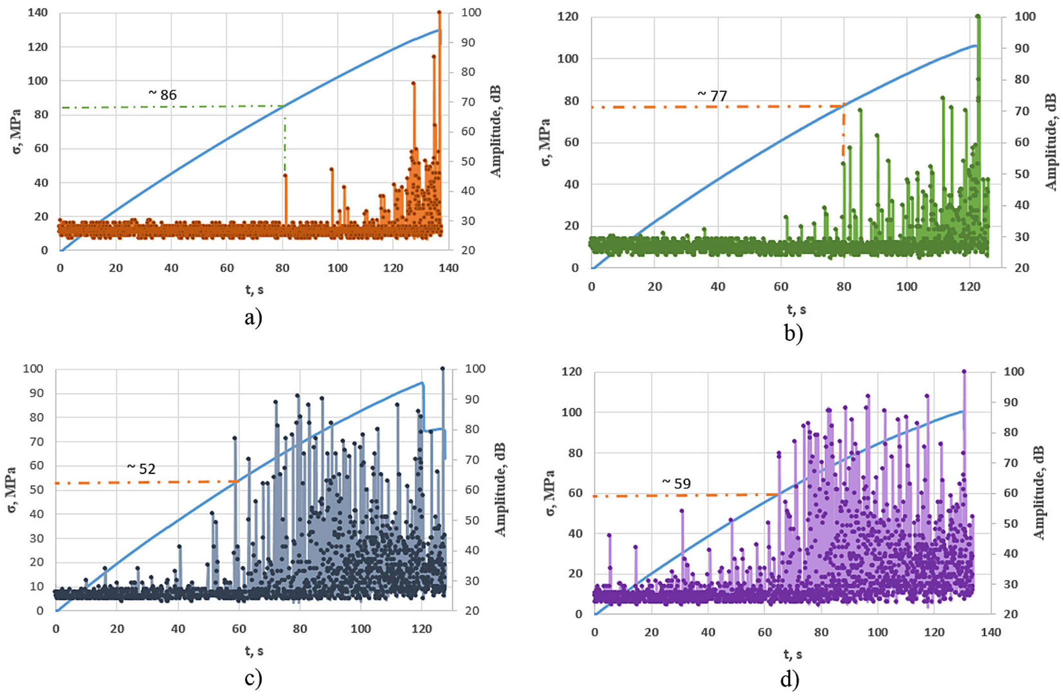


Figure 5. Graph of stress and amplitude as a function of time for a selected specimens: (a) K0 – without recyclate, (b) K1, (c) K2, (d) K3

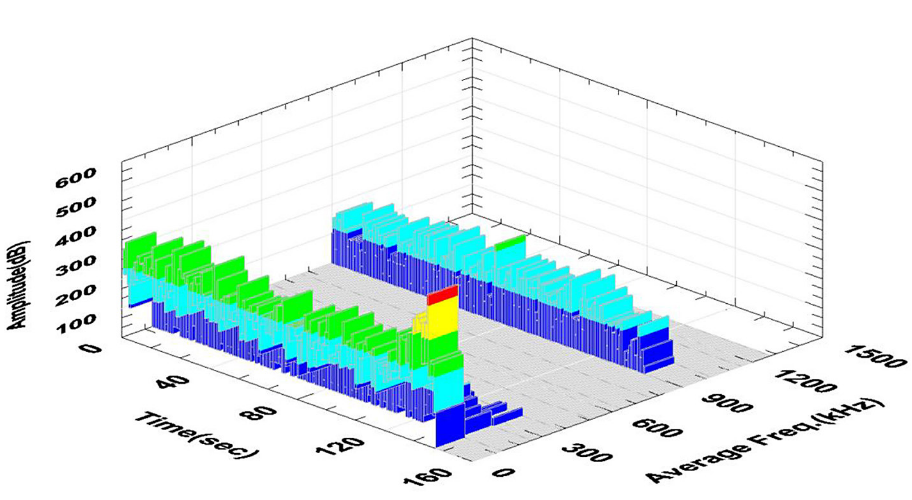
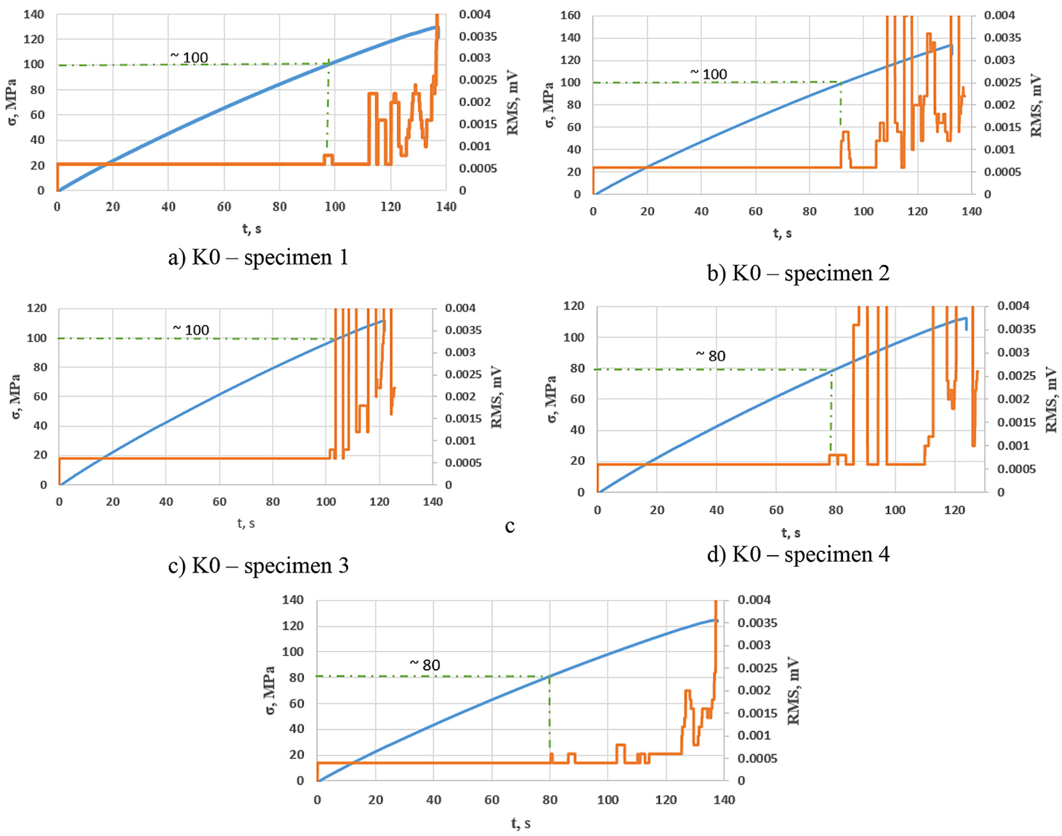


Figure 6. Example graph for sample K0 showing the change in signal amplitude and frequency as a function of time

especially in the case of the K2 and K3 composites. After analyzing the results obtained from the acoustic emission method for 5 samples from each plate, it was observed that the most repeatable parameter is RMS, which also provides diagnostic information. RMS is the effective value of a signal (periodic). Since average values are not used when describing periodic wave signals, the concept of RMS was introduced. It is a universal measure that we use regardless of the specificity of the signal being tested, its frequency and shape (wave). In order to precisely determine the value, 5 graphs will be presented for each sample, the stress values will be read and entered into the table, and then averaged (Figure 7).

Characteristic signal frequencies for the first signs of the destruction process (Figure 8) are about 270–300 kHz. Based on the analysis conducted using the RMS parameter for 5 samples of the composite without recyclate, it can be safely stated that these results are actually comparable. The stress values indicating the beginning of significant changes in the composite structure are in the range of 80–100 MPa, where for 3 samples out of 5 it is the same value. This confirms the validity of using the acoustic emission method to analyze the destruction process and at the same time determine the performance parameters for the structural composite. The first signs of the destruction process generate signals with an additional frequency of about 300 kHz (Figure 8). Figure 9 shows the stress analysis using the RMS parameter for sample K1.

Analyzing the results obtained for the K1 composite, the stress values at which significant structural changes occur in the composite are in the range of 61–66 MPa. These values can be considered comparable considering the technology of manufacturing the research materials (hand lamination) and the diversity of the obtained tensile strength (UTS) results (Table 2). A decrease in these parameters is certainly noticeable in relation to the K0 composite, without the addition of recyclate, but it is obvious, considering the lower content of reinforcement in the composite in relation to the material without recyclate. It also seems important to pay attention to the character of the RMS graphs, which are definitely more chaotic and diverse, in contrast to the composite without recyclate, which indicates a much greater



a) K0 – specimen 1

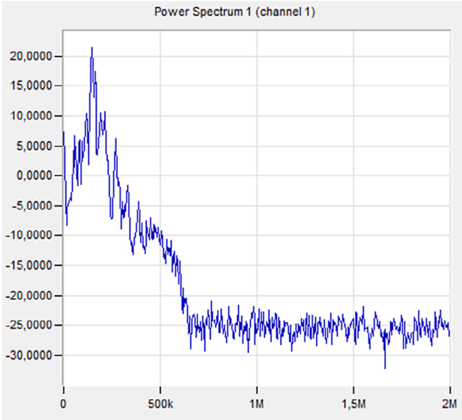
b) K0 – specimen 2

c) K0 – specimen 3

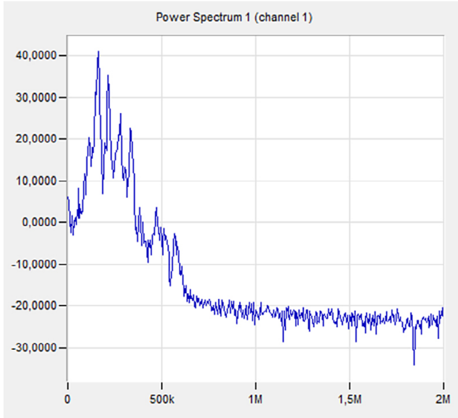
d) K0 – specimen 4

e) K0 – specimen 5

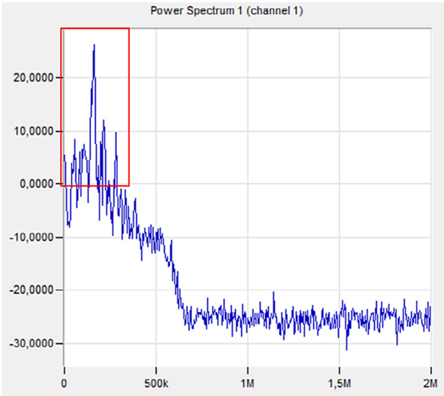
Figure 7. Graph of stress and RMS as a function of time for 5 selected specimens of K0



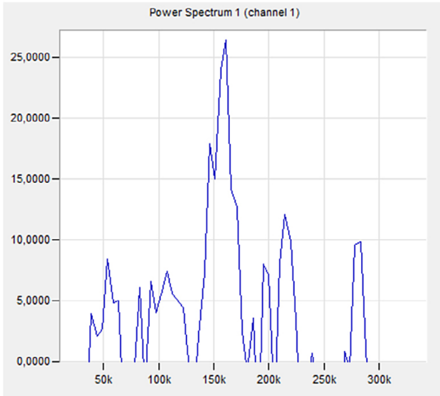
a) K0 – specimen 1



b) K0 – specimen 2



c) K0 – specimen 5



d) K0 – specimen 5 - enlarged graph

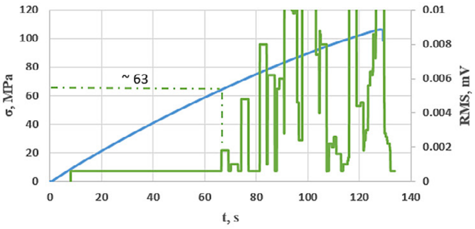
Figure 8. Examples of signals, after FFT analysis for the points marked in Figure 8 (Power vs Frequency)

number of events such as, among others, matrix cracking, fiber cracking, recyclate displacement in the matrix. Figure 10 shows examples of signals, after FFT analysis for the points marked in Figure 9 (Power vs Frequency).

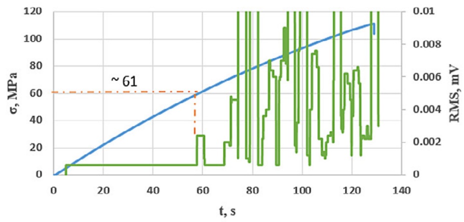
Characteristic signal frequencies for the first signs of the destruction process are lower than in the case of K0 (visible in the enlarged graph – signals with a frequency not higher than 220 kHz) (Figure 10). Figure 11 additionally shows an example graph for a sample of the change in the amplitude and average frequency of the signal as a function of time.

Figure 12 presents the stress analysis using the RMS parameter for the K2 sample. The obtained stress values are much more diverse than in the K1 composite and are in the range of 58 ÷ 68 MPa. These results are directly related to the nature of the distribution of the rubber recyclate in the composite and much greater inhomogeneity in the tested material, which is also shown by the nature of the RMS (t) graph (Figure 13). Characteristic signal frequencies for the first signs of the destruction process are lower than in the case of K0 and very similar to K1 (visible in the enlarged graph – signals with a frequency not higher than 270 kHz) (Figure 14).

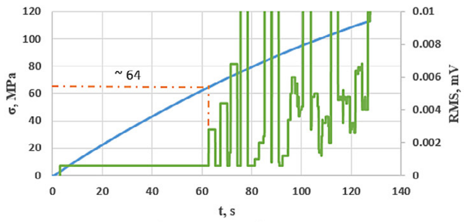
Low signal amplitude values in the initial phase of the test. Similarly to earlier, signals with a frequency above 500 kHz do not carry diagnostic information and are not considered. The graph shows that increasing stresses causing material degradation generate a signal not only with a higher amplitude but also with a higher frequency (as shown in the graphs after the FFT analysis – Power spectrum). Figure 15 shows the stress analysis using the RMS parameter for sample K3. Based on the obtained results of the values of the stresses in which damage initiation occurs for the K3 composite, their greater homogeneity and repeatability are noticeable, in contrast to the K2 composite. The values of the operating stresses are in the range of 62–70 MPa, but again, as in the case of the other results, the tensile strength for the tested composites and the manufacturing technology must be taken into account, which does not allow for the production of composites with 100% comparable results. The above-mentioned aspects also



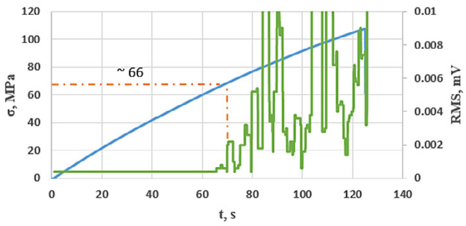
a) K1 – specimen 1



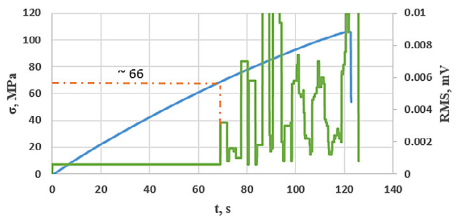
b) K1 – specimen 2



c) K1 – specimen 3

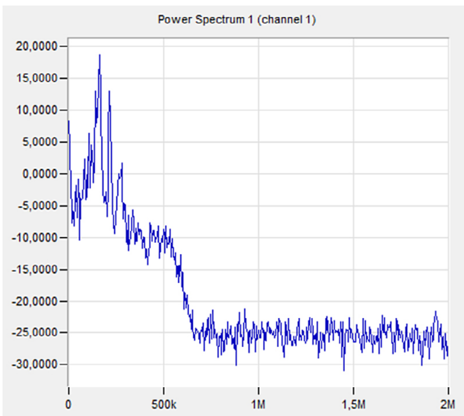


d) K1 – specimen 4

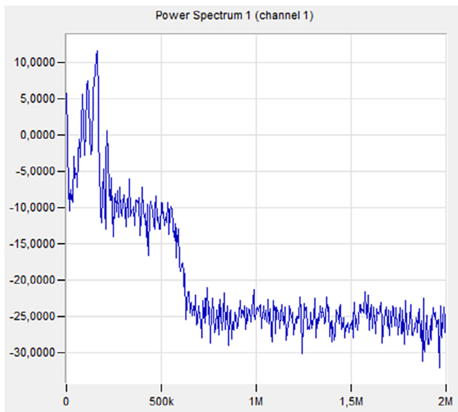


e) K1 – specimen 5

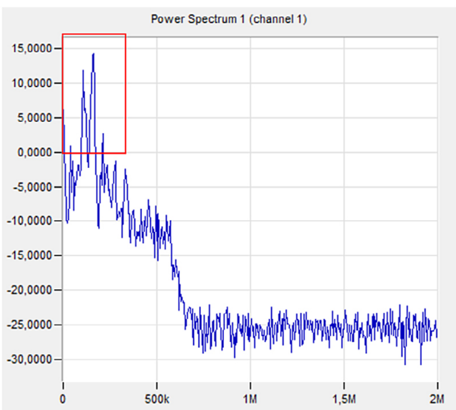
Figure 9. Graph of stress and RMS as a function of time for 5 selected specimens – K1



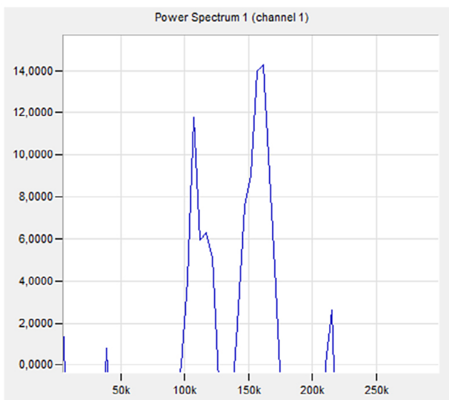
a) K1 – specimen 1



b) K1 – specimen 2



c) K1 – specimen 5



d) K1 – specimen 5 – enlarged graph

Figure 10. Examples of signals, after FFT analysis for the points marked in Figure 10 (Power vs Frequency)

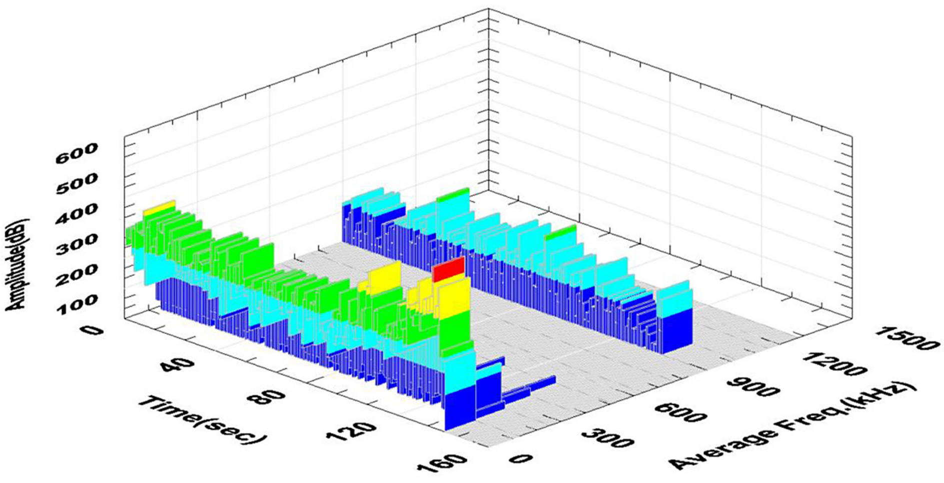


Figure 11. Example graph for a sample of the change in amplitude and mean frequency of a signal as a function of time for composite K1

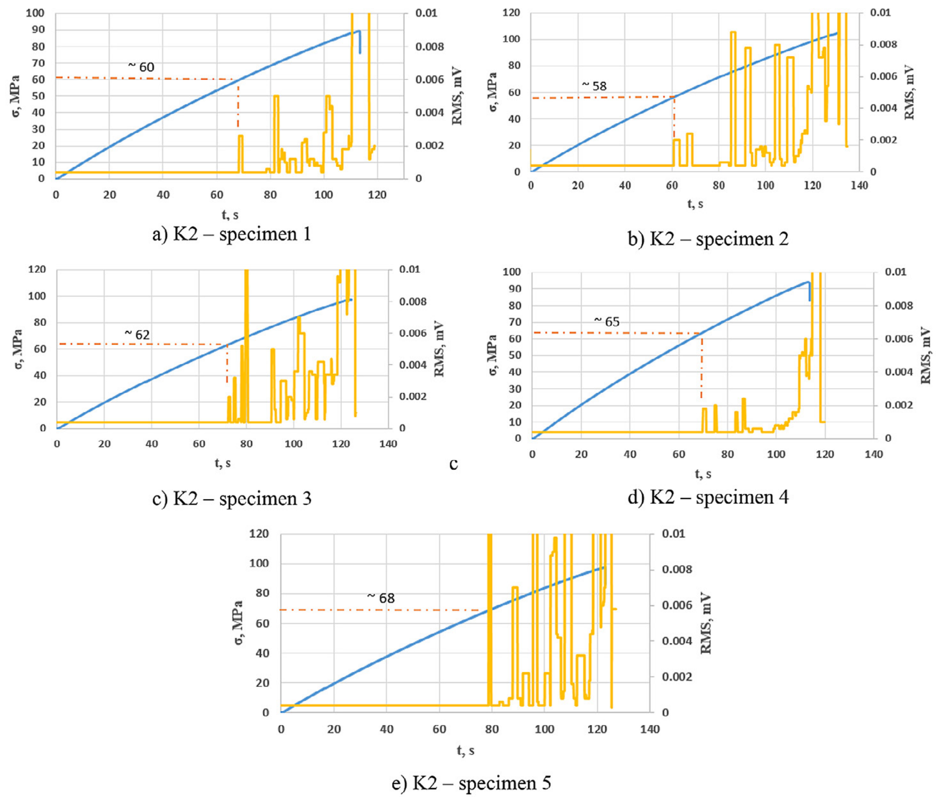
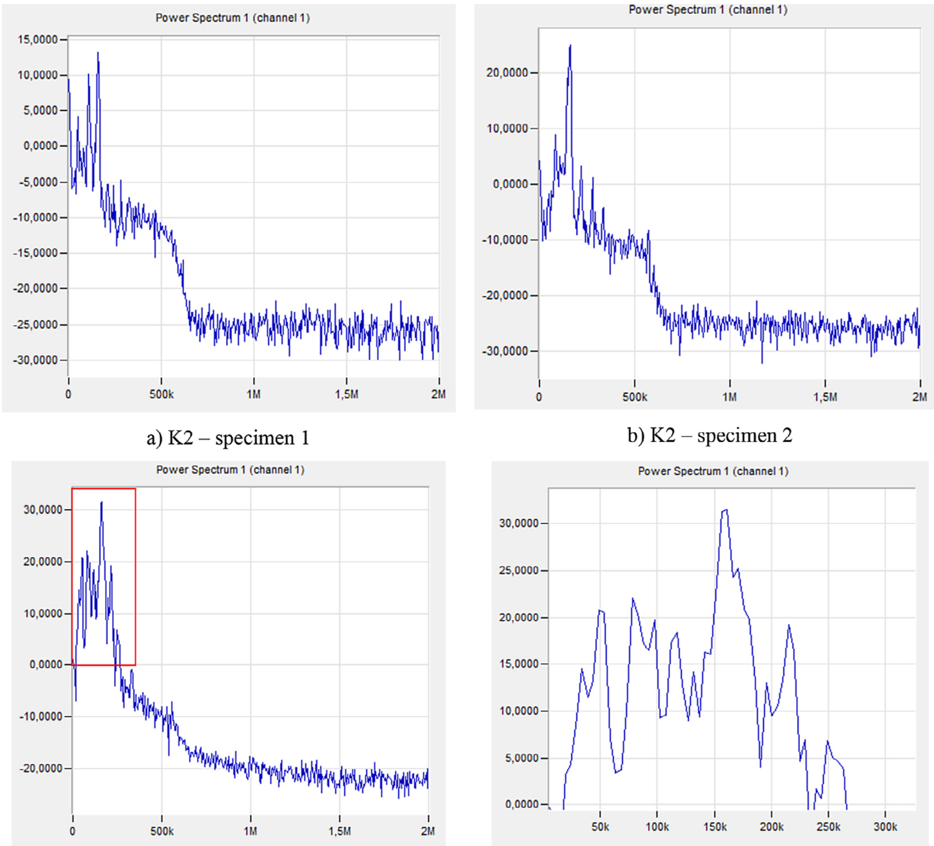


Figure 12. Graph of stress and RMS as a function of time for 5 selected specimens – K2

directly affect other tested parameters, which can be seen from the obtained results.

Similarly to K0, a signal with a frequency of about 350 kHz appears (the last graph (d) is an enlargement of a fragment of the one on the left) – all graphs have the same characteristic frequency (Figure 17). Low signal amplitude values in the initial phase of the test. Similarly to earlier, signals with a frequency above 500 kHz do not carry diagnostic information and are not considered. The graph shows that increasing stresses causing material degradation generate a signal not only with a higher amplitude but also with a higher frequency (as shown in the graphs after the FFT analysis – power spectrum). It is noticeable that the signal reaches higher frequencies compared to sample K2. Table 2 and Figure 18 present a summary of the obtained results.



a) K2 – specimen 1

b) K2 – specimen 2

c) K2 – specimen 5

d) K2 – specimen 5 – enlarge graph

Figure 13. Examples of signals, after FFT analysis for the points marked in Figure 13 (Power vs Frequency)

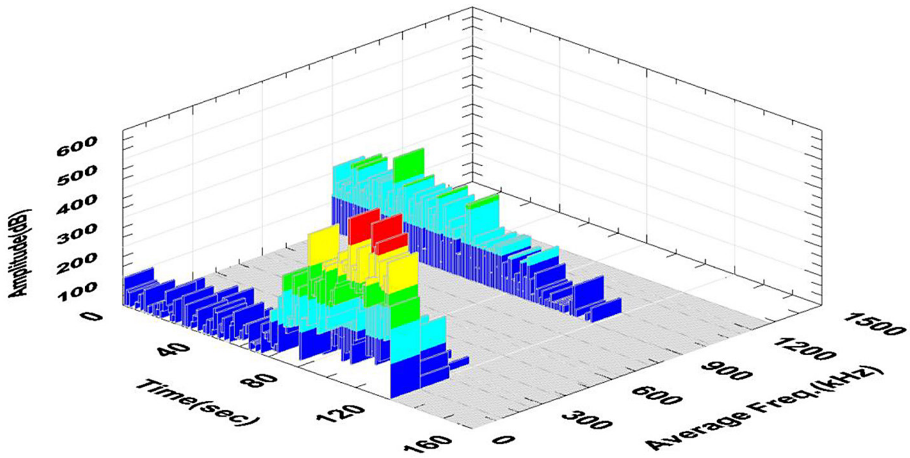
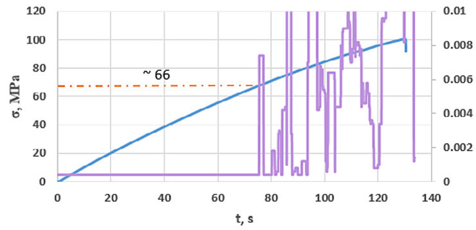


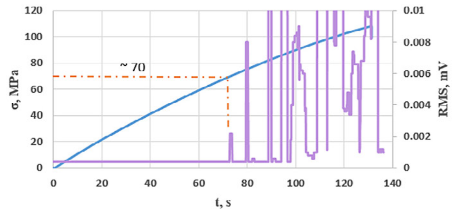
Figure 14. Example graph for a sample of the change in amplitude and mean frequency of a signal as a function of time for composite K2

Based on the obtained results of the values of "allowable" stresses in composite materials, it is noticeable that despite the earlier values indicating better parameters of the K1 composite, comparable results are also obtained for the K3 composite. Of the three tested materials, the K2 composite consisting of 2 layers of rubber recyclate has the lowest value. This indicates that the more even the waste distribution and its location in the center of the sample, the more it has a direct impact on the strength parameters.

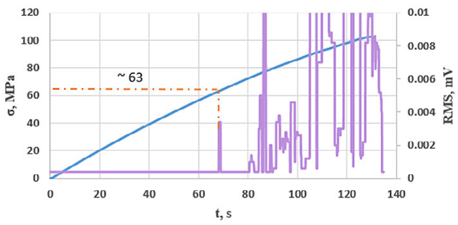
The results showed that the most favorable in terms of the distribution of the number of events is the composite with 1 layer of rubber



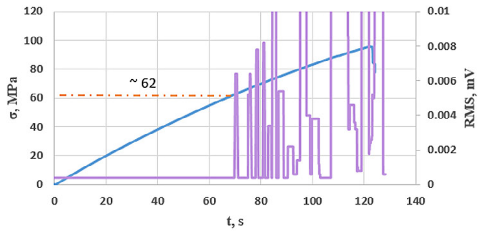
a) K3 – specimen 1



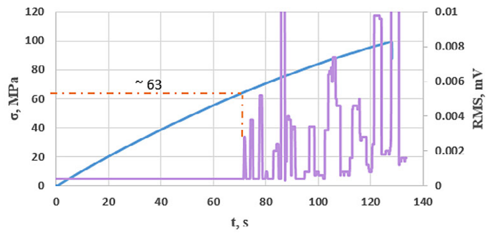
b) K3 – specimen 2



c) K3 – specimen 3

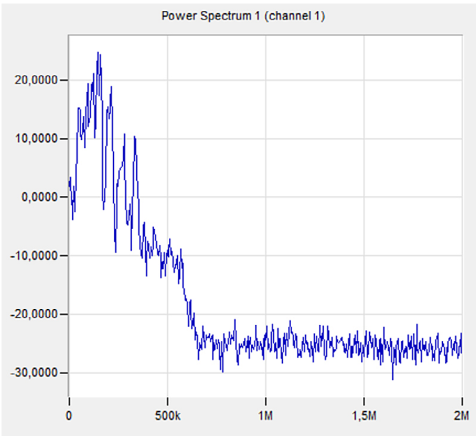


d) K3 – specimen 4

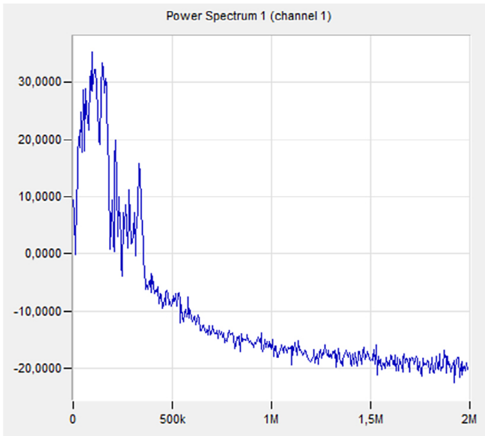


e) K3 – specimen 5

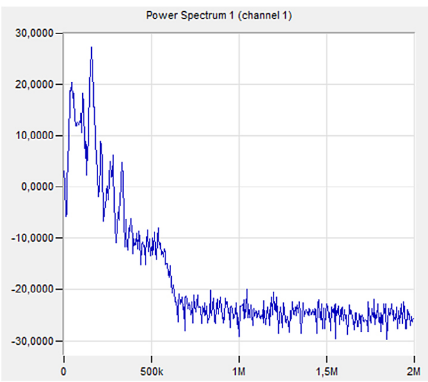
Figure 15. Graph of stress and RMS as a function of time for 5 selected specimens – K3



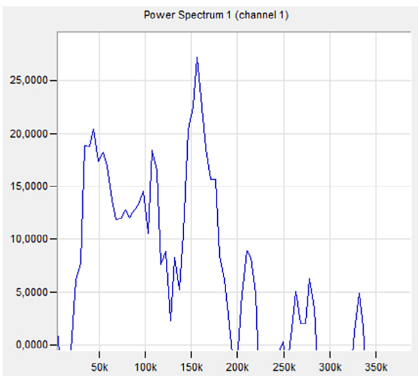
a) K3 – specimen 1



b) K3 – specimen 2



c) K3 – specimen 5



d) K3 – specimen 5 – enlarge graph

Figure 16. Examples of signals, after FFT analysis for the points marked in Figure 16 (power vs frequency)

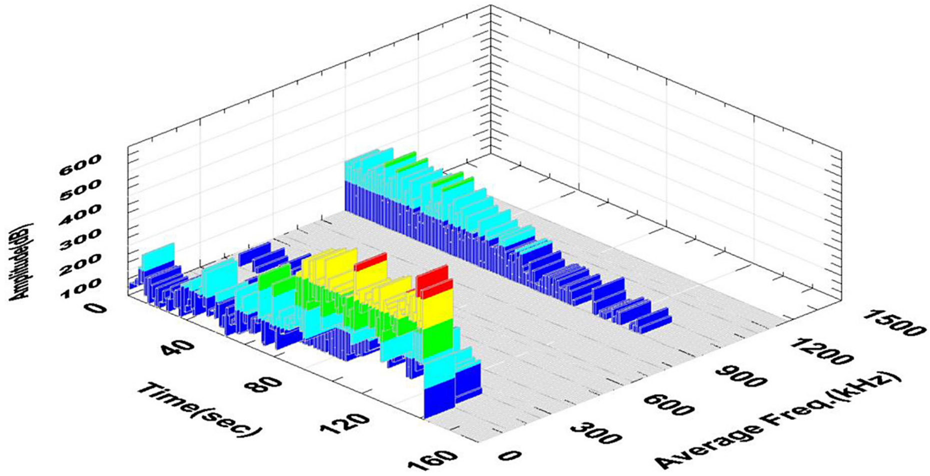


Figure 17. Example graph for a sample of the change in amplitude and mean frequency of a signal as a function of time for composite K3

Table 2. Summary of obtained stress results from RMS analysis

Sample	σ_{RMS}	UTS	Sample	σ_{RMS}	UTS	Sample	σ_{RMS}	UTS	Sample	σ_{RMS}	UTS
	MPa	MPa		MPa	MPa		MPa	MPa		MPa	MPa
K0 - 1	100	130	K1 - 1	63	105	K2 - 1	60	90	K3 - 1	66	100
K0 - 2	100	130	K1 - 2	61	110	K2 - 2	58	103	K3 - 2	70	105
K0 - 3	100	110	K1- 3	64	110	K2- 3	62	97	K3- 3	63	103
K0 - 4	80	115	K1 - 4	66	110	K2 - 4	65	95	K3 - 4	62	97
K0 - 5	80	120	K1 - 5	66	105	K2 - 5	68	97	K3 - 5	63	100
Average value	92	121	Average value	64	108	Average value	62.6	96	Average value	64.8	101
Standard deviation	9.79	8	Standard deviation	1.90	2.45	Standard deviation	3.56	4.17	Standard deviation	2.93	2.76

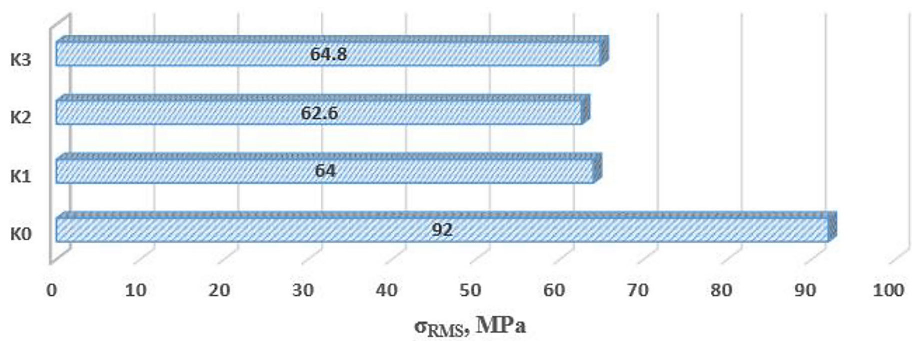


Figure 18. Summary of the obtained stress results, depending on the arrangement of the recyclate layers in the composite

recyclate (K1), while the least favorable is the K2 composite with two layers, distributed symmetrically. The characteristics of the number of events, despite the addition of recyclate, do not differ significantly in the case of the K1 and K2 composites, which seems to be advantageous in terms of the use of these materials as structural. The analysis of the amplitude parameter did not allow for the reading of unambiguous parameters for the sample without the addition of recyclate and with one of its layers. However, there are increases in the amplitude, especially in the case of the K2 and K3 composites. Based on these and previous studies, it was found that the most repeatable parameter is RMS. In the case of sample K0, the stress values indicating the beginning of important changes in the composite structure are in the range of 80–100 MPa. These changes constitute the beginning of damage initiation, which leads to further deformation in the material. In the case of composite K1, the stress values at which significant structural changes occur in the composite are in the range of 61 ÷ 66 MPa. A decrease in these parameters is certainly noticeable in relation to composite K0, without the addition of recyclate, but this is obvious, considering the lower content of reinforcement in the composite in relation to the material without recyclate [30].

CONCLUSIONS

In this article, a number of parameters from the acoustic emission method were analyzed and correlated with strength parameters in order to assess the effect of the distribution of the rubber recyclate layers in the composite. The nature of the RMS graphs is much more chaotic and diverse, in contrast to the composite without recyclate, which indicates a much greater number of events such as, among others, matrix cracking, fiber cracking, recyclate displacement in the matrix. For composite K2, the stress values are much more diverse than in composite K1 and are in the range of 58 ÷ 68 MPa. Based on the obtained results of the values of the stresses at which damage is initiated for the K3 composite, their greater homogeneity and repeatability are noticeable, in contrast to the K2 composite. The values of the operating stresses are in the range of 62 ÷ 70 MPa. Based on the read average values of the stresses at which damage is initiated in the composite materials, it is noticeable that despite the earlier values indicating better parameters of the K1 composite, comparable results are also obtained for the K3 composite. Of the three tested materials, the K2 composite consisting of 2 layers of recyclate rubber is characterized by the lowest value. In conclusion, the more even the distribution of waste and its location in the center of the sample, the more it has a direct impact on the strength parameters, however, the obtained values are relatively comparable, which allows us to state that the main factor influencing the operating parameters is the % content of recyclate rubber in the composite.

REFERENCES

1. Fazli A., Rodrigue D., Waste rubber recycling: a review on the evolution and properties of thermoplastic elastomers, Materials (Basel). 2020 Feb; 13(3): 782.
2. Ramarad S., Khalid M., Ratnam C., Chuah A.L., Rashmi W. Waste tire rubber in polymer blends: A review on the evolution, properties and future. Prog. Mater. Sci. 2015; 72: 100–140. https://doi.org/10.1016/j.pmatsci.2015.02.004
3. Karger-Kocsis J., Mészáros L., Bárány T. Ground tyre rubber (GTR) in thermoplastics, thermosets, and rubbers. J. Mater. Sci. 2013; 48: 1–38. https://doi.org/10.1007/s10853-012-6564-2
4. Ikeda Y., Kato A., Kohjiya S., Nakajima Y. Rubber Science. Springer; Berlin/Heidelberg, Germany: 2018.
5. Fukumori K., Matsushita M., Okamoto H., Sato N., Suzuki Y., Takeuchi K. Recycling technology of tire rubber. JSAE Rev. 2002; 23: 259–264. https://doi.org/10.1016/S0389-4304(02)00173-X
6. Medina N.F., Garcia R., Hajirasouliha I., Pilakoutas K., Guadagnini M., Raffoul S. Composites with recycled rubber aggregates: Properties and opportunities in construction. Constr. Build. Mater. 2018; 188: 884–897. https://doi.org/10.1016/j.conbuildmat.2018.08.069
7. Amari T., Themelis N.J., Wernick I.K. Resource recovery from used rubber tires. Resour. Policy. 1999; 25: 179–188. https://doi.org/10.1016/S0301-4207(99)00025-2
8. Akbas, A.; Yuhana, N.Y. Recycling of rubber wastes as fuel and its additives. Recycling 2021; 6: 78. https://doi.org/10.3390/recycling6040078
9. Shah J., Jan M.R., Mabood F. Catalytic conversion of waste tyres into valuable hydrocarbons. J. Polym. Environ. 2007; 15: 207–211. https://doi.org/10.1007/s10924-007-0062-7
10. Fang Y., Zhan M., Wang Y. The status of recycling of waste rubber. Mater. Des. 2001; 22: 123–128. https://doi.org/10.1016/S0261-3069(00)00052-2.; Adhikari B., De D., Maiti S. Reclamation and recycling of waste rubber. Prog. Polym. Sci. 2000; 25: 909–948. https://doi.org/10.1016/S0079-6700(00)00020-4
11. Adhikari B., De D., Maiti S. Reclamation and recycling of waste rubber. Prog. Polym. Sci. 2000; 25: 909–948. https://doi.org/10.1016/S0079-6700(00)00020-4
12. Singh N., Hui D., Singh R., Ahuja I., Feo L., Fraternali F. Recycling of plastic solid waste: A state of art review and future applications. Compos. Part B Eng. 2017; 115: 409–422. https://doi.org/10.1016/j.compositesb.2016.09.013
13. Chittella H., Yoon L.W., Ramarad S., Lai Z., Rubber waste management: A review on methods,

mechanism, and prospects, Polymer Degradation and Stability, 2021; 194. https://doi.org/10.1016/j.polymdegradstab.2021.109761

14. Moreno T., Balasch A., Bartrolí R., Eljarrat E., A new look at rubber recycling and recreational surfaces: The inorganic and OPE chemistry of vulcanised elastomers used in playgrounds and sports facilities, Science of The Total Environment, 2023; 868. https://doi.org/10.1016/j.scitotenv.2023.161648
15. Abramczyk N., Żuk D., Panasiuk K., Analysis of the influence of adding rubber recyclate on the strength properties of epoxy-glass composites, Journal of KONBIN, 2023; 53: 1.
16. Abramczyk, N., Żuk, D., Panasiuk, K., Dyl, T., Influence of the type of layered distribution of rubber recyclate as an additive modifying the mechanical properties of epoxy-glass composites, Archives of Materials Science and Engineering, 2022; 118(2): 61–66.
17. Abramczyk, N., Żuk, D., Czech, A., Charchalis, A., Using statistical analysis to assess the impact of the addition of rubber recyclate on the strength properties of the epoxy-glass composite, Journal of Achievements in Materials and Manufacturing Engineering, 2023; 121(1): 77–92.
18. Żuk, D., Abramczyk, N., Charchalis, A., Analysis of the impact of rubber recyclate addition to the matrix on the strength properties of epoxy–glass composites, Polymers, 2023; 15(16): 3374.
19. Panasiuk, K., Dudzik, K., Hajdukiewicz, G., Abramczyk, N., Influence of gamma-phase aluminum oxide nanopowder and polyester–glass recyclate filler on the destruction process of composite materials reinforced by glass fiber, Polymers, 2024; 16(16): 2276.
20. Abramczyk, N., Drewing, S., Panasiuk, K., Żuk, D., Application of Statistical Methods to Accurately Assess the Effect of Gamma Aluminum Oxide Nanopowder on the Hardness of Composite Materials with Polyester–Glass Recyclate, Materials, 2022; 15(17): 5957.
21. Panasiuk, K., Dudzik, K., Hajdukiewicz, G., Acoustic emission as a method for analyzing changes and detecting damage in composite materials during loading, Archives of Acoustics, 2021; 46(3): 399–407.
22. Available online: https://krisko.lublin.pl/chemia/zywice-poliestrowe-polimal/maty-tkaniny-rowingi/maty-szklane (accessed on 15 March 2025).
23. Available online: https://orzelsa.com/pl/zaklad-produkcji-granulatu-gumowego/ (accesed on 15 March 2025).
24. Abramczyk, N., Hajdukiewicz, G., Charchalis, A., Żuk, D. Application of Kolmogorov–Sinai's metric entropy for the analysis of mechanical properties in the bending test of epoxy–rubber–glass composites. Materials 2024; 17: 5079. https://doi.org/10.3390/ma17205079
25. PN-EN ISO 527-4:2000. Plastics - Determination of mechanical properties under static stretching - Test conditions for isotropic and orthotropic fiber-reinforced plastic composites.
26. Panasiuk, K., Dudzik, K. Determining the stages of deformation and destruction of composite materials in a static tensile test by acoustic emission. Materials 2022; 15: 313. https://doi.org/10.3390/ma15010313
27. PN-EN 1330-9:2017-09. Non-destructive testing - Terminology - Part 9: Terms used in acoustic emission testing.
28. PN-EN 13554: 2011E. Non-destructive testing - Acoustic emission - General rules.
29. PN-EN 15857: 2010E. Non-destructive testing - Acoustic emission - Testing of fiber-reinforced polymers - Specified methodology and general evaluation criteria.
30. Aggelis, D., Barkoula, N.-M., Matikas, T., Paipetis, A., Acoustic structural health monitoring of composite materials : Damage identification and evaluation in cross ply laminates using acoustic emission and ultrasonics. Composites Science and Technology, 2012; 72(10): 1127–1133. https://doi.org/10.1016/j.compscitech.2011.10.011