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USE OF 3D OPTICAL TECHNIQUES IN THE ANALYSIS OF THE EFFECT OF ADDING RUBBER RECYCLATE TO THE MATRIX ON SELECTED STRENGTH PARAMETERS OF EPOXY–GLASS COMPOSITES

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ABSTRACT: The article presents a method of modifying the strength properties of epoxy–glass composite by changing the percentage composition of the matrix by the addition of rubber recyclate. Taking into account environmental protection and economic conditions in the process of recycling and utilisation of waste, it is advisable to look for applications of non-degradable waste materials. Based on epoxy resin, a glass mat with a random direction of fibres and rubber recyclate, a test material with different percentage compositions was produced. Samples from the manufactured materials were subjected to a static tensile test on a ZwickRoell testing machine using the ARAMIS SRX measuring system. In addition, CT (computerized tomography) scans of the inside of the samples were made using a ZEISS METROTOM 6 Scout tomograph, and observations of the internal structures were made using a scanning electron microscope. The use of optical and microscopic techniques enabled the precise determination of strength parameters of the examined composites and the analysis of the behaviour of samples under load. The analysis of deformations over time in the examined samples showed a beneficial effect of the addition of rubber recyclate on the elastic properties of the examined composites.

Keywords: epoxy–glass composites, ARAMIS SRX, static tensile test, rubber recyclate, 3D optical techniques

1. INTRODUCTION

Epoxy–glass composites are modern construction materials that have been used for years in many industries, i.e. construction, automotive, aviation or yacht industry [1–3]. These materials have a wide spectrum of possibilities for modification of their mechanical properties, obtained by changing their structure or using various types of additives and fillers [2, 4, 5].

As additives for composites with glass matt reinforcement, various types of materials of both inorganic and natural origin are used [6–8]. In most of the solutions used in composite materials, the addition of recyclate is aimed at using the maximum amount of rubber additive as a filler and flexible material with a limited range of strength parameters of finished elements [2, 23, 24]. In the latest scientific research, rubber recyclate obtained from car tires is used as an additive or filler for polymers [9–11]. However, there is a lack of research on the addition of rubber recyclate to epoxy–glass composites.

The use of rubber recyclate as a component of new epoxy–glass composite materials is very important from the perspective of environmental protection because it reduces the amount of harmful waste. Using rubber recyclate allows obtaining a new composite material with unknown properties that can be verified through strength tests.

The use of 3D optical techniques enables measurements and analyses of deformations both in large and in small samples of materials [8–10]. Digital image correlation (DIC) measurements using optical methods are particularly useful in composite materials for which numerical analysis in programs based on the finite element method is difficult due to their anisotropy [11]. In the case of a composite with the addition of rubber recyclate, the creation of the FEM (Finite Element Method) numerical model is complicated and time-consuming. Observation of sample deformations using 3D optical techniques enables obtaining information on the behaviour of materials under load, as well as precise determination of their strength parameters. In the case of deformation analysis of composites with the addition of rubber recyclate, it is important to take into account the voids in the cross-section of the samples used in the static tensile test. These voids result in a change in the value of the cross-sectional area of the sample in the measuring part, which assumes the load during stretching. The determination of the actual stress values that appear in materials during the test as well as Young modulus is more precise and accurate using 3D optical techniques in the case of an anisotropic material, which is a composite with the addition of rubber recyclate. By scanning the samples with the ZEISS METROTOM 6 Scout tomograph, we can accurately determine the values of cross-sectional areas, and thus obtain information on the strength of materials closer to reality than that obtained from the software of the testing machine.

Systems of optical measurement techniques are often used in the analysis of the properties of composite materials. The article in Ref [12] presents the possibilities of using the ARAMIS system in the fatigue strength analysis of aircraft structures. In the study in Ref [13], examples of validation of meso-FE (meso-scale finite element)models of carbonepoxy and glass/polypropylene composites were shown. DIC was used in these studies to record distortions in the full field. In the article in Ref [14], it was analysed based on measurements using the ARAMIS system, the mechanical and acoustic properties of starch–hemp composites, including the mechanism of cracking and sample damage. Working with optical systems, i.e. ARAMIS, also enables monitoring of composite damage; in the article in Ref [15], three techniques are combined to search for correlations during incremental cyclic tensile tests of glass fibre-reinforced polymers. In Ref [16], ARAMIS optical deformation analysis was used in direct tensile tests to observe crack propagation in SHCC (strain-hardening cement composite) materials. In article in Ref [17], using the ARAMIS optical deformation measurement system, the intensity of surface deformations at various load levels was analysed and used to indicate the location and geometrical characteristics of both external and internal damage. The research in Ref [18] indicated the great potential of the DIC technique in determining the fracture toughness of concrete composites with the addition of FA (class F fly ash). In this study, based on data from the ARAMIS program, the values of fracture mechanics parameters were determined, which allowed observing the behaviour of the structural material precisely at the time of initial cracking.

We used optical measurement techniques to determine and analyse the strength properties of new epoxy–glass composites by the addition of rubber recyclate. The use of the ARAMIS SRX system, similar to studies in Ref [12, 13, 17], allows obtaining information on the properties and strength parameters of materials, while we additionally extended the scope of the present research by scanning using a ZEISS METROTOM 6 Scout tomograph to verify the actual Young E modulus values of new composite materials.

For an anisotropic material, the generalised Hooke law written in the summation convention is expressed as follows:

$$\varepsilon_j = S_{jk}\sigma_k$$

where S_{jk} is the material compatibility matrix, and j, k = 1, 2,...,6 (j denotes stress directions and k denotes the direction of the corresponding deformation).

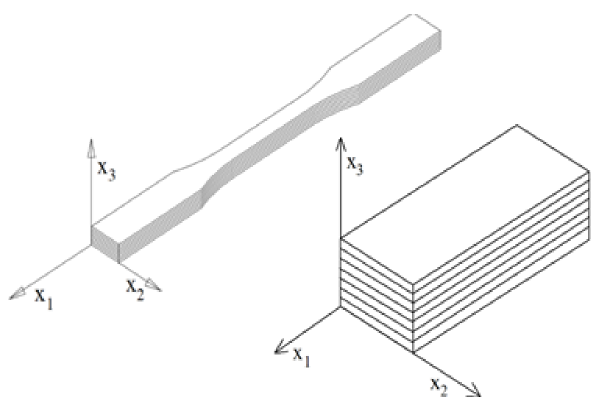

Fig. 1. Orientation in the coordinate system of the measuring part of the sample [19]

In the literature on the description of the properties of composites, the index designations 1, 2, and 3 are used, corresponding to the coordinate axis systems (Fig. 1). Only for orthotropic materials, the components of the compliance tensor can be represented by engineering constants in the form of a matrix using the matrix described in Eq. (1). The numerical solution to such a problem leads to considerable difficulties. Using modern imaging tools that record the course of strength tests, the solution and determination of the sought values are much simpler.

$$S = \begin{bmatrix} \frac{1}{E_1} & -\frac{\nu_{21}}{E_2} & -\frac{\nu_{31}}{E_3} & 0 & 0 & 0 \\ -\frac{\nu_{12}}{E_1} & \frac{1}{E_2} & -\frac{\nu_{32}}{E_3} & 0 & 0 & 0 \\ -\frac{\nu_{13}}{E_1} & -\frac{\nu_{23}}{E_2} & \frac{1}{E_3} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{32}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{13}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}} \end{bmatrix} \quad (1)$$

The measurements presented in the article using 3D optical techniques allowed verifying the values of the parameters obtained from a ZwickRoell stretching machine. The analysis of the obtained results showed differences in the measurements of significant values characterising the elastic and strength properties of the tested materials, which resulted from the accuracy of the measurement of stresses appearing in the cross-sections of the analysed variants of the samples.

2. DESCRIPTION OF THE TESTED MATERIAL AND RESEARCH METHODOLOGY

2.1. Properties of the used rubber recyclate

Recycling rubber products is a technologically complex process. In addition to rubber, a car tire contains steel reinforcement and fibres, while the rubber compound in addition to rubber includes components such as soot, silica, kaolin, chalk, lit stone, plasticisers, anti-ageing agents, flame retardants and vulcanising assembly (sulphuric or peroxide).

Rubber recyclate is obtained by processing used car tires. One of the most common methods of recycling rubber from car tires is mechanical shredding, which involves breaking tires into smaller fragments. They are then cleaned of metals and other foreign materials such as fabrics and wires. After cleaning, the rubber granules obtained from the crushed rubber can be used to produce new products. A diagram of the recycling process of rubber recyclate from car tyres is presented in Fig. 2.

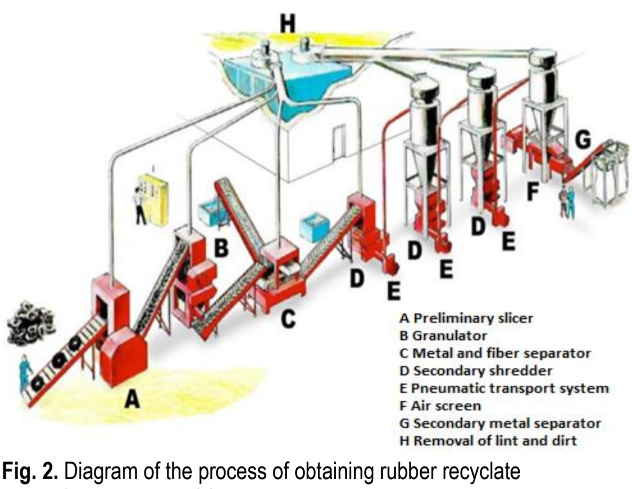

Fig. 2. Diagram of the process of obtaining rubber recyclate from car tyres [24]

Rubber recyclate derived from processed car tires with a grain size of 0–3 mm was used for this study. The recyclate was pre-sieved using a LAB 11-200 laboratory sieve shaker from EKOLAB (Fig. 3) to precisely separate its various fractions. As an addition to the matrix of composites, a recyclate fraction with a grain size from 0.5 mm to 1.5 mm was used. The percentage composition and physicochemical parameters of the rubber recyclate used in the tested materials are presented in Tabs 1 and 2. The chemical composition of the tyre tread does not differ from the chemical composition of the rubber granules obtained in the recycling process [25].

Tab. 1. Percentage composition of rubber recyclate [26]

Ingredient	Content (%)
Natural rubber	15
SBR	20
BR	10
IIR/XIIR (butyl and halogenated butyl rubber)	5
Silica	15
Soot	15
Sulphur	2
Resin	2
Mineral and vegetable oils	10
Other (zinc oxide, stearic acid)	6

BR, butadiene rubber; SBR, styrene-butadiene rubber**.**

Tab. 2. Physical and chemical properties of rubber recyclate used in materials [26]

Parameter	Value
Density	360–370 kg/m^3
Flash point	>350 °C
Thermal decomposition	>180 °C

2.2. Creation of research materials

The test materials were manufactured based on an EM 1002/300/125 structural glass mat, with random fibre distribution and a mass of 350 g/m^2. This mat was made of cut strands of glass fibre glued together with an emulsion binder. Epoxy resin Epidian@ 6 with a Z-1 hardener was used as the matrix of the composite. The composition of the epoxy resin used is presented in **Błąd! Nieprawidłowy odsyłacz do zakładki: wskazuje na nią samą.**. The components of the research materials are shown in Figs **Błąd! Nie można odnaleźć źródła odwołania.** and 4.

As the base material about which the results obtained from other variants of composites were compared, the *K0* composite was used, which is a material without the addition of rubber recyclate. The *K0* composite consisted of 12 layers of glass mat successively filtered with Epidian® 6 resin mixed in a predetermined proportion with the Z-1 hardener. In all made composites, a hardener in an amount of 13 g/100 g of warp was added. The weight share of the glass mat in the material *K0* was 40%.

Based on these materials and a selected fraction of rubber recyclate with a grain size from 0.5 mm to 1.5 mm, four variants of research materials were produced: K0 – pure epoxy–glass composite without the addition of recyclate, K3 – composite containing 3% rubber recyclate and variants K5 and K7 containing, respectively, 5% and 7% of the weight volume of the recyclate additive to the composite matrix.

Tab. 3. Epidian® 6 Epoxy resin characteristics

Parameter	Unit	Value
Epoxy number	[Mol/100 g]	0.510–0.540
Density at 25 °C	[g/cm^3]	1,17
Viscosity at 25°C	[mPa*s]	1,000–1,500
Gel time of 100 g at 20°C	[min]	20
Hardness time at 20°C	[days]	7

Fig. 3. Components of manufactured research materials

Fig. 4. Sieve shaker LAB-11-200 with separated rubber recyclate fractions

Composite research plates were made by hand lamination with the use of constant double-sided pressure for all variants. For manual lamination, a rectangular steel mould with dimensions of 300 mm × 900 mm, brushes and rollers were used. Standardised test samples were produced from the prepared boards. Fig. 5 shows the geometry of the samples obtained after using the water-cutting method. The cut samples were subjected to a static tensile test on a ZwickRoell testing machine using the ARAMIS

SRX measuring system and scanning with a ZEISS METROTOM 6 Scout tomograph.

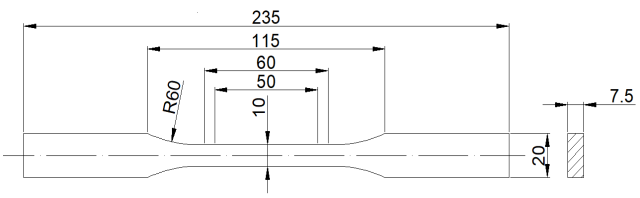

Fig. 5. Shape and dimensions of samples to be tested

Fig. 6 shows the process of manufacturing the K5 material by manual lamination. Fig. 7 shows samples of the K3 material prepared for the static tensile test. Tab. 4 shows the percentage composition of the manufactured variants of composite materials.

Fig. 6. Manufacture of materials by hand lamination

Fig. 7. Test samples cut by water cutting

Tab. 4. Mass content of the components of the epoxy–glass composite with the addition of rubber recyclate to the matrix, made by hand lamination

Material significa-tion	Number of glass mat layers	Resin content (%)	Content of the glass mat (%)	Rubber recyclate content (%)
K0	12	60	40	0
K3	12	60	37	3
K5	12	60	35	5
K7	12	60	33	7

3. PLANNING AND CONDITIONS OF THE EXPERIMENT

The samples, before being fixed in the holders of the testing machine, were pre-prepared by coating them with white and black paints. This made it possible to carry out measurements using the ARAMIS SRX system during the static tensile test. During the test, two cameras of the ARAMIS SRX system recorded deformations occurring on the surfaces of the samples. Fig. 8 shows the K0 material composite samples prepared for testing, covered with paint, Fig. 9 shows the K0 sample mounted on the holders of the ZwickRoell testing machine, and the ARAMIS SRX measuring system recording the deformations appearing on the surface of the samples in real-time during the static tensile test. In addition, all samples were measured using a ZEISS METROTOM 6 Scout tomograph with a 3k X-ray detector. This detector has a 225 kV X-ray source and an X-ray detector with a resolution of 3,008 × 2,512 pixels. Thanks to the CT scans of the analysed samples, it was possible to visualise the internal structures of the tested materials. Because a tomograph scan allows for the detection of material defects, pores and cavities in the material, it was possible to determine the actual cross-sectional areas of the tested samples and the actual stress values based on the obtained CT scans. For each of the tested composite samples, models were developed in GOM Suite software based on imaging using the ARAMIS SRX system and CT scans. The analyses allowed obtaining information about the exact values of the strength parameters of the tested materials.

Fig. 8. Samples prepared for measurements using the ARAMIS SRX system

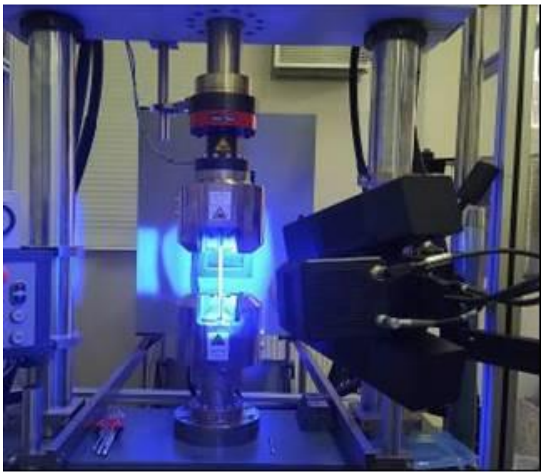

Fig. 9. Research using the ARAMIS SRX camera system

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3.1. Measurements and analysis using electron microscopy SEM

A SEM (Scanning electron microscope) Zeiss EVO MA 15 was used to study the microstructures of the composites (Fig. 10). The device allows obtaining electron images of samples with a resolution of 3 nm at a voltage of 30 kV. The range of possible magnifications is from 5 to 1,000,000 times. The microscope allows the observation of samples weighing up to 500 g (with full mobility of the microscope table in XYZ directions) or up to 5 kg (then the movement of the table is limited to directions along the XY axis). The aim of the observation of microstructures of composite materials was to determine the influence of rubber recyclate content on the microstructure and thus on the mechanical properties. The research was carried out on cut pieces of samples from each composite. The cross-sectional surfaces were prepared using 320, 800 and 1,200 gradation abrasive papers, and then polished with a 3 μm diamond polishing slurry.

Figs 11–14Fig. 14

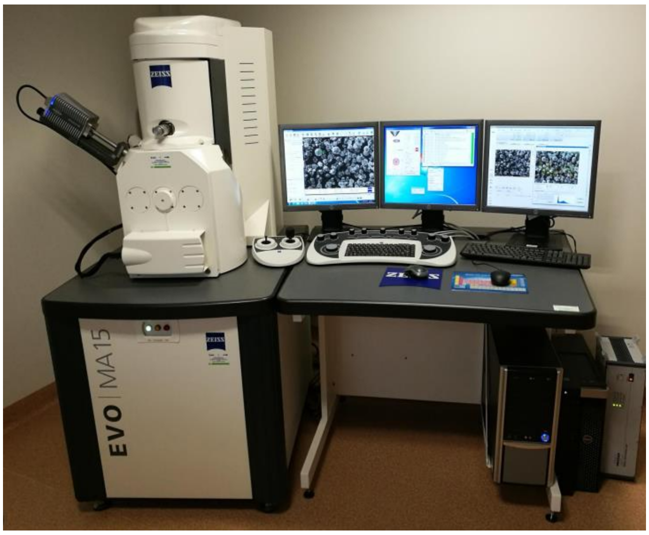


Fig. 10. Scanning electron microscope Zeiss EVO MA 15 used to observe the microstructure of the tested materials

a) b)

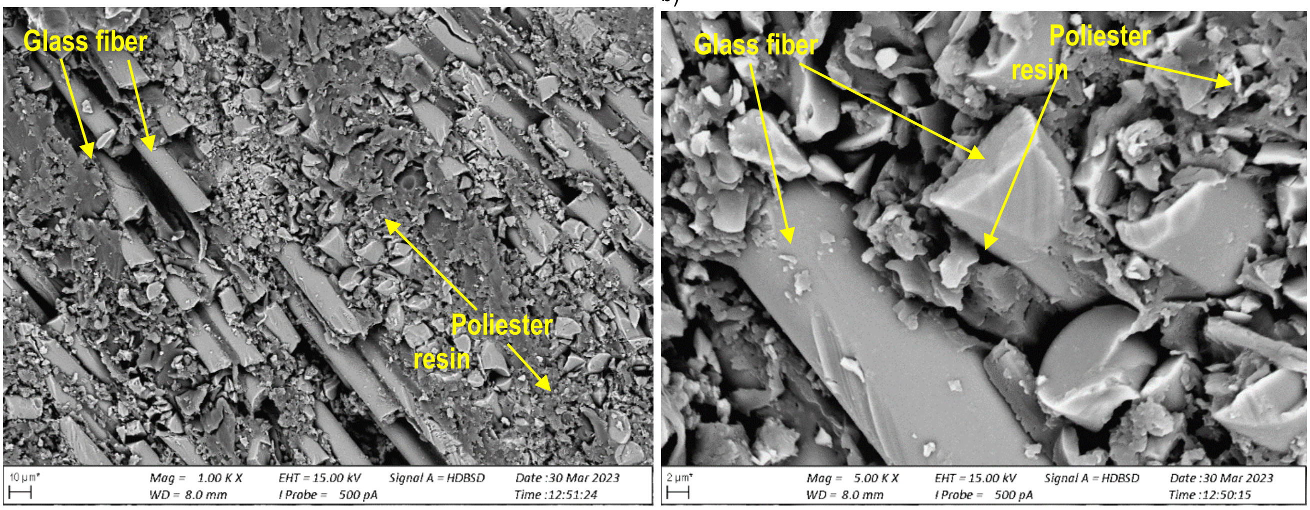


Fig. 11. Structures of composite materials: a) Composite K0, area 1000x; b) Composite K0, area 5000x

a) b)

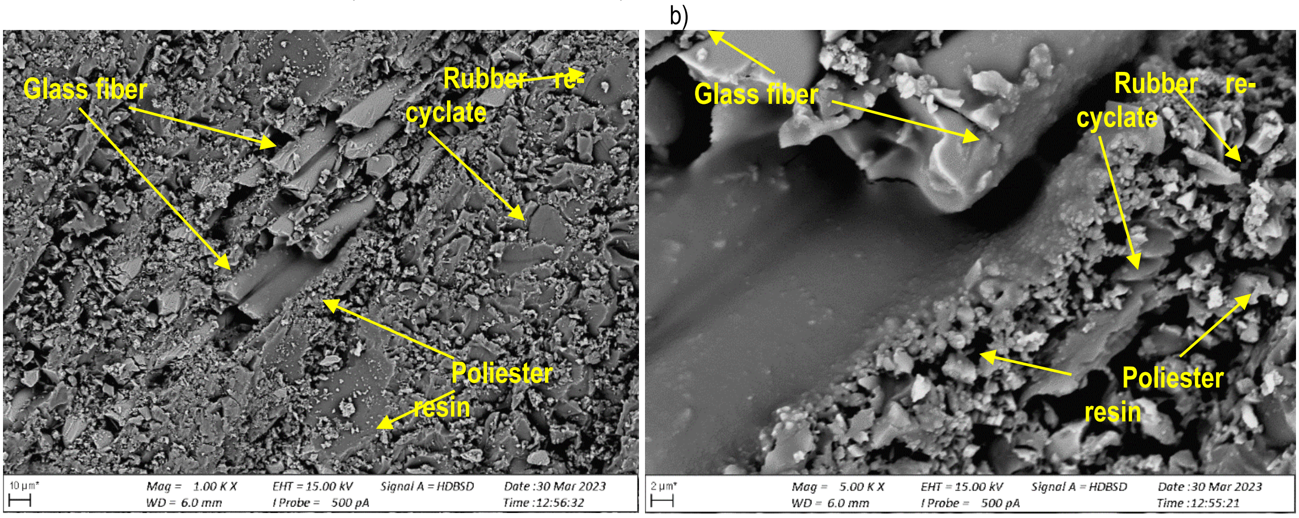


Fig. 12. Structures of composite materials :a) Composite K3, area 1000x; b) Composite K3, area 5000x

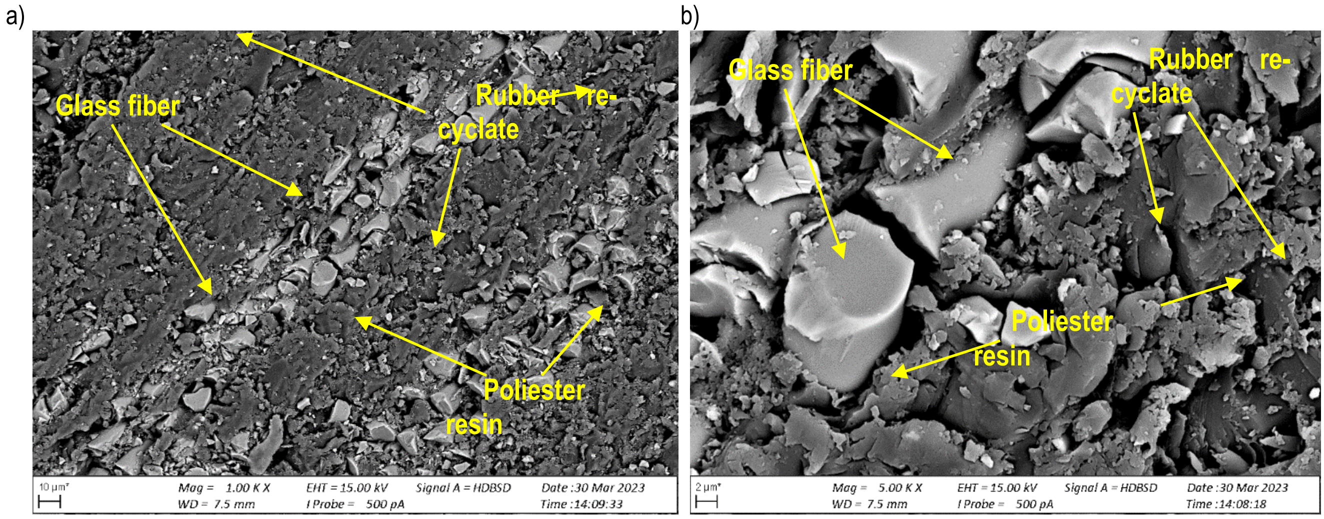


Fig. 13. Structures of composite materials: a) Composite K5, area 1000x; b) Composite K5, area 5000x

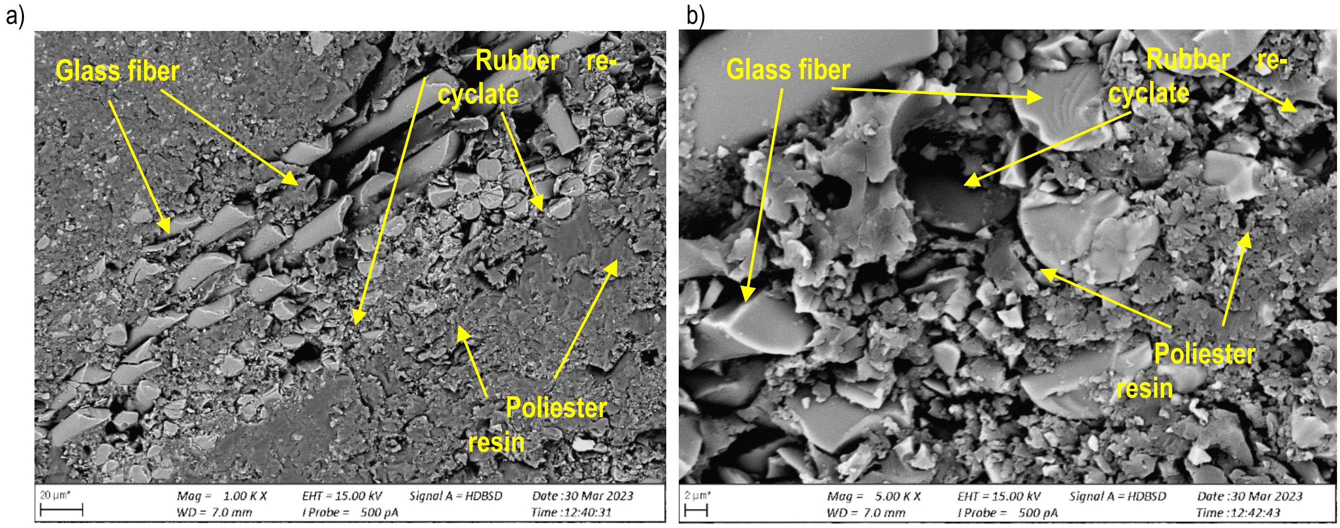


Fig. 14. Structures of composite materials: a) Composite K7, area 1000x; b) Composite K7, area 5000x

Based on the obtained images of structures, for a composite with 3%, 5% and 7% content of rubber recyclate, there is a difference in structure compared to K0 composites – without the addition of recyclate. In microstructures, the effect of rubber recyclate on the adhesion of the resin to glass fibres can be noticed. For the K3 material, the adhesion between the resin with rubber recyclate and reinforcement is greater than that in the case of K5 and K7 materials, although small air pores are visible. Comparing these materials with the K0 composite, the effect of recyclate on the structure between successive layers of reinforcement can be noticed. Microscopic observations showed that the addition of rubber recyclate has a significant impact on the structure of the examined materials. In Figs. 12–14, there are grains of recyclate, surrounded by the pores of the ventilation formed around them and at the interface of the glass mat resin. Air pores weaken the bond between the reinforcement and the resin, which may affect the strength parameters of K3, K5 and K7 composites.

4. RESULTS OF EXPERIMENTAL RESEARCH AND THEIR ANALYSIS

The obtained test results made it possible to determine the effect of the addition of rubber recyclate to the composite matrix on changes in the strength properties of the samples. The strength parameters were obtained from the ZwickRoell testing machine and GOM Suite 2021 software.

4.1. Analysis of the results obtained from the TestXpert II software of the ZwickRoell testing machine

Fig. 15 shows a graph from the static tensile test of the tested composite samples obtained from TestXpert II software of the ZwicRoell testing machine. The list of parameters obtained for the tested composite materials from TestXpert II software is presented in Tab. 5.

Tab. 5. Strength parameters obtained from TestXpert software of the ZwickRoell machine for epoxy–glass composite materials based on Epidian® 6 resin with the addition of rubber recyclate, randomly, to the matrix

Material	σ_m [MPa]	*ε* [%]	*E* [MPa]
K0	112.38	1.75	7,930
K3	96.46	2.09	5,978
K5	103.85	1.97	6,632
K7	94.92	2.14	5,874

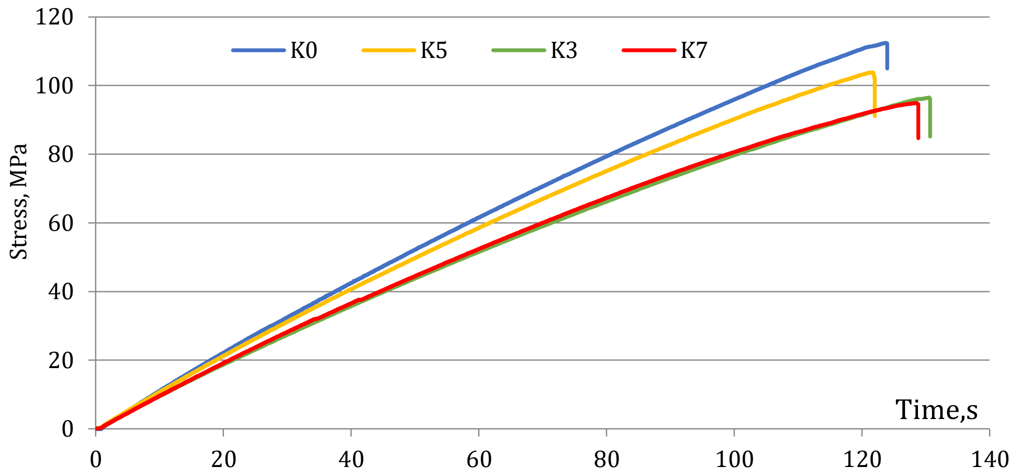


Fig. 15. Graph of the static tensile test of the tested composite materials obtained from the ZwickRoell testing machine

Analysing the results obtained from TestXpert II software, it was found that the highest strength parameters in comparison with a pure composite were obtained for the K5 material containing 5% of rubber recyclate. For this material, the Young modulus E value decreased by 16.4% compared to the E value of the K0 material. For the K3 and K7 materials, the values of the Young modulus E decreased by more than 25% compared to the E value of pure composite K0. It is worth noting the beneficial effect of adding rubber recyclate to the matrix of composites on their susceptibility to deformation, which is defined by the value of parameter ε. The value of this parameter in all variants of the composite with the addition of rubber recyclate to the matrix increased. The highest increase in the value of the ε parameter compared to the ε value for the pure K0 composite was recorded for the K7 sample; this increase was of the order of 22.3%. The lowest increase was recorded for the K5 variant; in this case, the ε value increased by 12.6% compared to the ε value for the K0 composite. In the case of the analysis of the tensile strength σm, the variants of the composite with the addition of rubber recyclate reached lower values than those of the pure composite. The variant of the K5 material was the best because for it the decrease in the value of σm was only 7.6% compared to that of the pure K0 composite. Tab. 6 presents a list of percentage increases and decreases in strength parameters obtained from TestXpert II software for K3, K5 and K7 materials about the pure K0 epoxy–glass composite.

Tab. 6. Values of percentage changes in the strength parameters of composites with the addition of rubber recyclate about the K0 composite (Data from Test Xpert II software)

Material	σm [MPa]	ε [%]	E [MPa]
K3	14.2	–19.4	24.6
K5	7.6	–12.6	16.4
K7	15.5	–22.3	25.9

4.2. Analysis of the results obtained from GOM Suite 2021 software

During the static tensile test, the ARAMIS SRX system recorded the deformations appearing on the samples in a real-time test. From the obtained records, files were obtained, on which GOM Suite 2021 software was based. The data obtained from GOM Suite 2021 software made it possible to read the values and graphically display the deformations appearing on the surface of the samples during the stretching process. An example of such imaging is shown in Fig. 16.

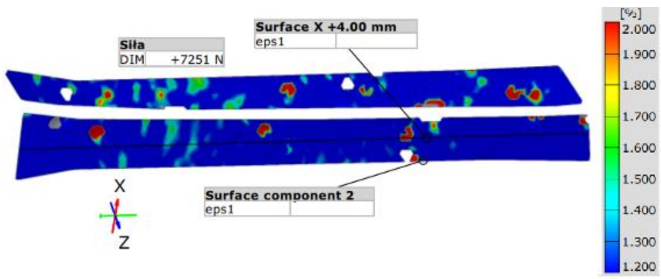


Fig. 16. Map of principal strains of the K3 sample subjected to a static tensile test obtained in the GOM Suite program

The analysis of the results obtained in GOM Suite software provided information on the mechanical properties of the tested materials and the behaviour of the samples under load conditions. After entering the data from the ZwickRoell machine on the tensile force and data on the geometry of the samples into GOM Suite software and performing a series of calculations, information on the values of strength parameters and changes in deformations occurring during the test were obtained for each sample. An example of parameter values obtained from GOM Suite software for the K7 sample is shown in Fig. 17.

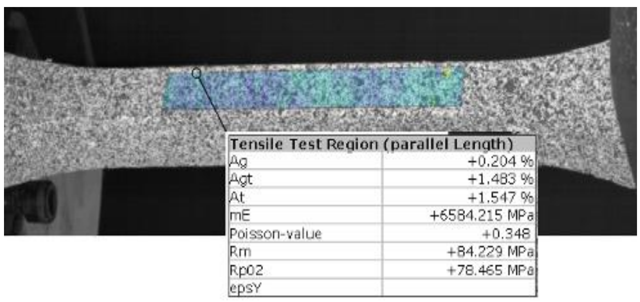


Fig. 17. Values of strength parameters obtained based on GOM Suite software for the K7 sample

Tab. 7 presents the values of strength parameters obtained during the static tensile test with the ARAMIS SRX system and GOM Suite software for the tested material variants.

Tab. 7. Values of strength parameters obtained during a static tensile test with the use of the ARAMIS SRX system (obtained from GOM Suite 2021)

Parameter	K0	K3	K5	K7
Ag [%]	0.317	0.204	0.320	0.204
E [MPa]	8,391	6,812	7,084	6,584
υ [–]	0.334	0.350	0.298	0.348
Rm [MPa]	118.57	84.47	92.93	84.23

During the analysis of the results obtained from GOM Suite software, it was found that the addition of rubber recyclate to the resin reduces the strength parameters of the epoxy–glass composite. The Young modulus decreased compared to the value of this modulus for the K0 material: in the case of the addition of 3% recyclate by about 19%, with the addition of 5% recyclate, the modulus decreased by about 16%, and in the case of the addition of 7% recyclate, it decreased by 21%. A similar trend was maintained for tensile strength values. This parameter has decreased for the variant K3 by 29% compared to the Rm value for the pure K0 composite, which decreased by 22% for the K5 variant, and by 29% for the K7 variant. At the same time, a beneficial effect of the addition of rubber recyclate on the elasticity and deformation method of the tested composite materials was observed. For each of the variants of the K3, K5 and K7 materials, the value of the Poisson number increased compared to that of the base material. These values increased by a maximum of 5% for the variant K3. Such a change in the elasticity of the material is caused by the impact of an additional component with elastic properties greater than that of the pure composite. The comparison of percentage decreases and increases of materials with the addition of rubber recyclate to the pure K0 composite based on data from GOM Suite software is presented in Tab. 8.

Tab. 8. Values of percentage changes in the strength parameters of composites with the addition of rubber recyclate about the K0 composite (Data from GOM Suite software)

Parameter	Percentage changes of strength parameters of samples K3, K5 and K7 about K0 material		
	K3	K5	K7
Ag [%]	–35.65	+0.95	–35.65
E [MPa]	–18.82	–15.58	–21.53
υ [–]	+4.79	–10.78	+4.19
Rm [MPa]	–28.76	–21.62	–28.96

4.3. Analysis of the results obtained from scanning samples with the ZEISS METROTOM 6 Scout tomograph

To precisely determine the strength parameters of the new composite materials, and in particular the values of the Young modulus *E*, the inside of the tested samples was X-rayed using a ZEISS METROTOM 6 Scout tomograph. Fig. 12 shows the image of the obtained CT scans of the samples made using a tomograph. These measurements allowed for the analysis of the internal structure of the tested materials. Based on this, we can obtain information about the distribution of granulation inside the samples and to determine the size of the actual cross-sectional areas. The purpose of the analyses performed using CT scans was to find the smallest cross-section. This was carried out by creating several dozen cross-sections in 2-mm steps (black lines in Fig. 18b), and then by analysing the cross-sectional area (taking into account voids in the structure), the smallest cross-section was found (red lines in Fig. 18b). Using values of the actual cross-sectional areas obtained, thanks to the CT scans, we can determine the tensile strength of the tested samples after taking into account the voids in the internal space of the material caused by the presence of rubber recyclate grains.

(a)

(b)

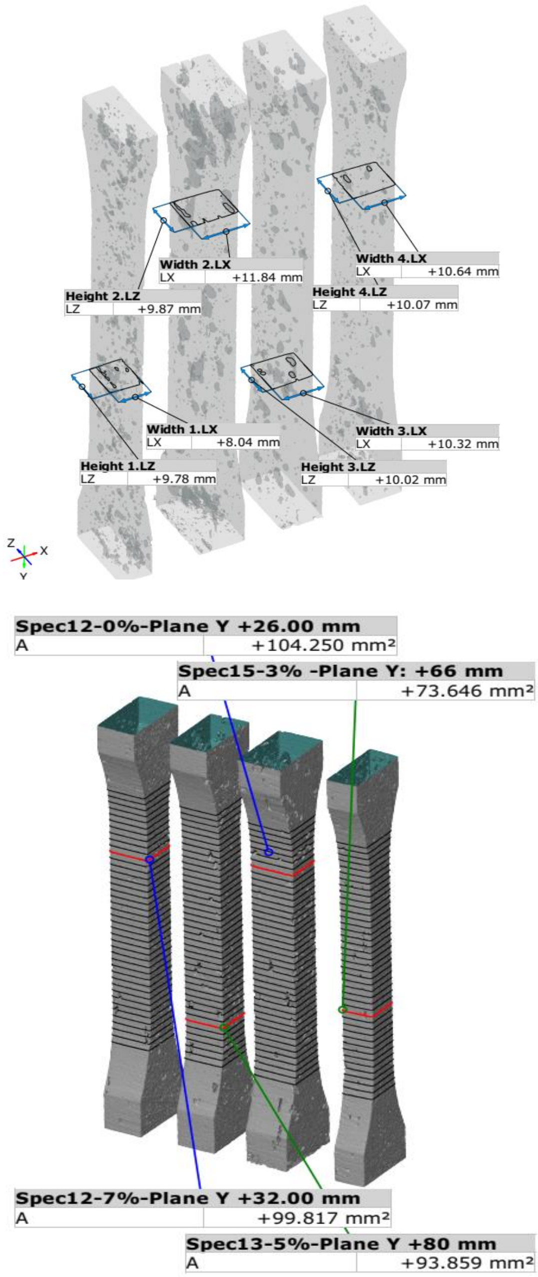


Fig. 18. (a) View of the external sections of the analysed samples obtained with the ZEISS METROTOM 6 Scout (GOM CT) tomograph; (b) Values of actual cross-sectional areas obtained with GOM Suite software

Fig. 19a–c and d present a summary of differences in the stress analysis for the tested samples about the actual cross-sectional area of the sample (from data based on CT scans after taking into account the recyclate in the cross-section). There are three tensile curves in each graph, and the stress and s values obtained from TestXpert II and GOM Suite software (for files from the ARAMIS SRX system and CT scans) were compared.

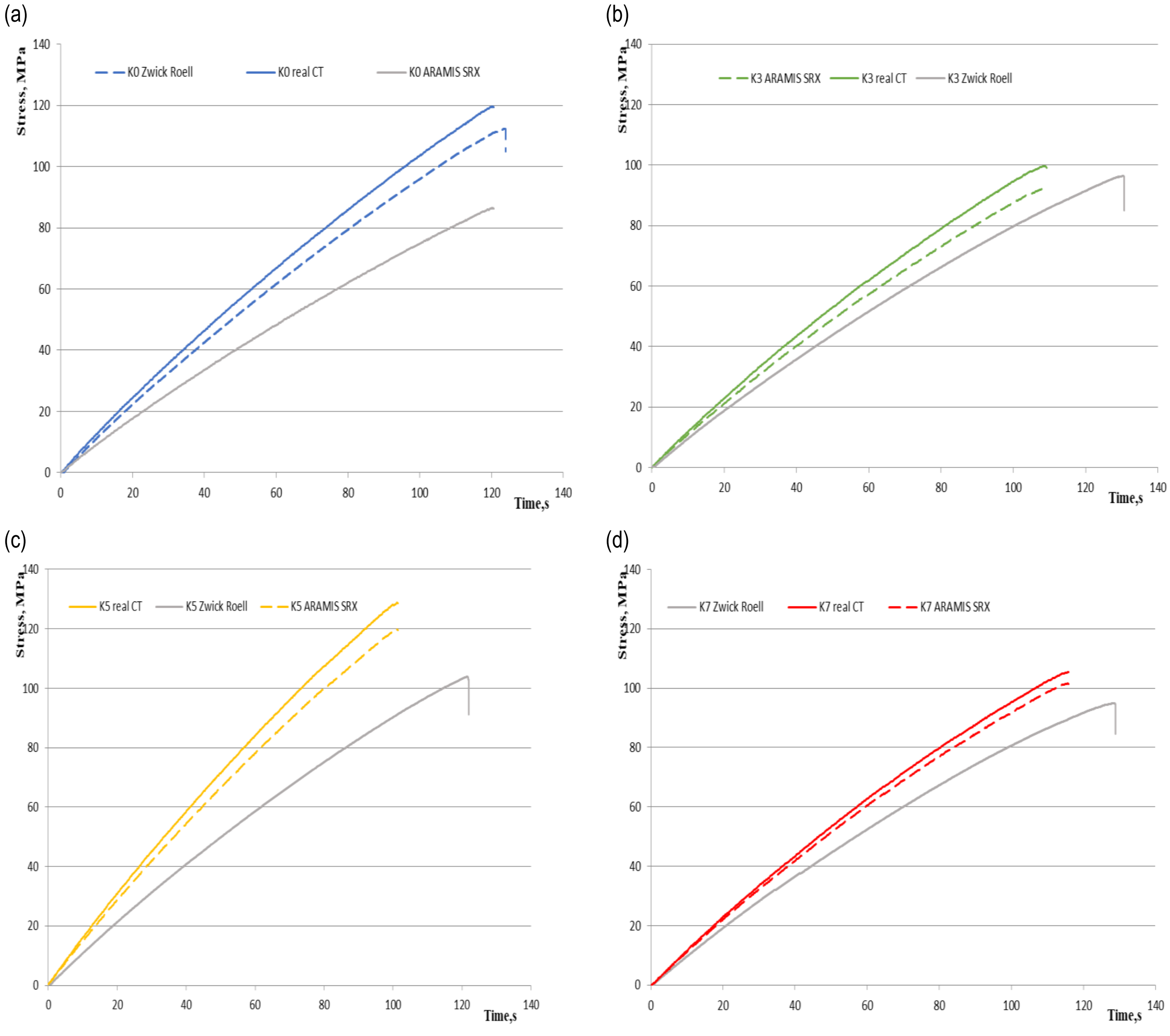


Fig. 19. Differences in the stress values in the samples after taking into account the actual cross-sectional areas, thanks to the CT scans made for the samples: a) without recyclate addition; b) with 3% recyclate addition; c) with 5% recyclate addition; d) with 7% recyclate addition

Fig. 20 presents a summary of the obtained test time–stress diagrams, taking into account the minimum real external cross-section, taking into account voids and without taking into account voids. Section Analyses with and without voids were performed by GOM Suite software based on measurements made with the ZEISS METROTOM 6 Scout. The diagram also shows the minimum cross-sections corresponding to the places of stress calculation.

The performed CT scans allowed illustrating the differences in the actual stress values that the analysed research materials can transfer. The new composite material, which is an epoxy–glass composite with the addition of rubber recyclate, is a unique combination of the strength properties of the resin with the elastic properties of the rubber recyclate.

Fig. 21 presents the lists of the obtained tensile strength values for the tested variants of materials, depending on the measurement method used. The presented values vary significantly. The essence of these differences is taking into account the actual cross-sectional areas of the tested samples in their measuring parts in the calculations.

As a result of the analysis of the Rm values obtained from Test Xpert II software of the testing machine and after the use of optical measurement techniques, it can be concluded that the addition of rubber recyclate significantly affects the strength parameters of the obtained composites. Rubber recyclate grains creating voids in cross-sections affect the reduction of stress values that the material can transfer. This reduction is only visible after CT scans. After taking into account the values of the actual cross-sectional areas obtained from CT scans, a decrease in the Rm parameter of 24% was noted for the K5 material compared to the Rm value for the K5 material obtained after measurements using the ARAMIS SRX system, which were based on the external dimensions of the samples in their measuring parts. The summary of the obtained Rm values for the tested composite materials is presented in Tab. 9.

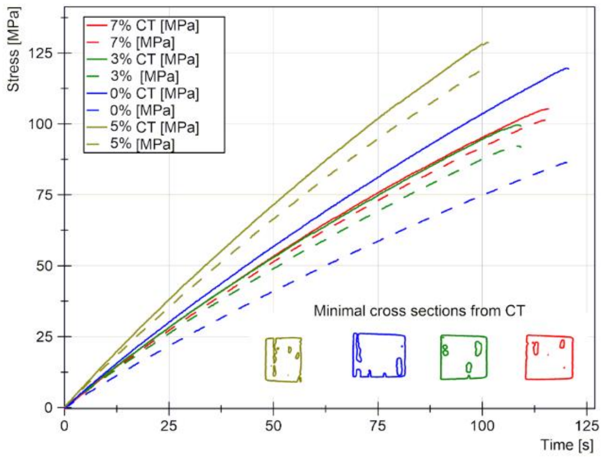
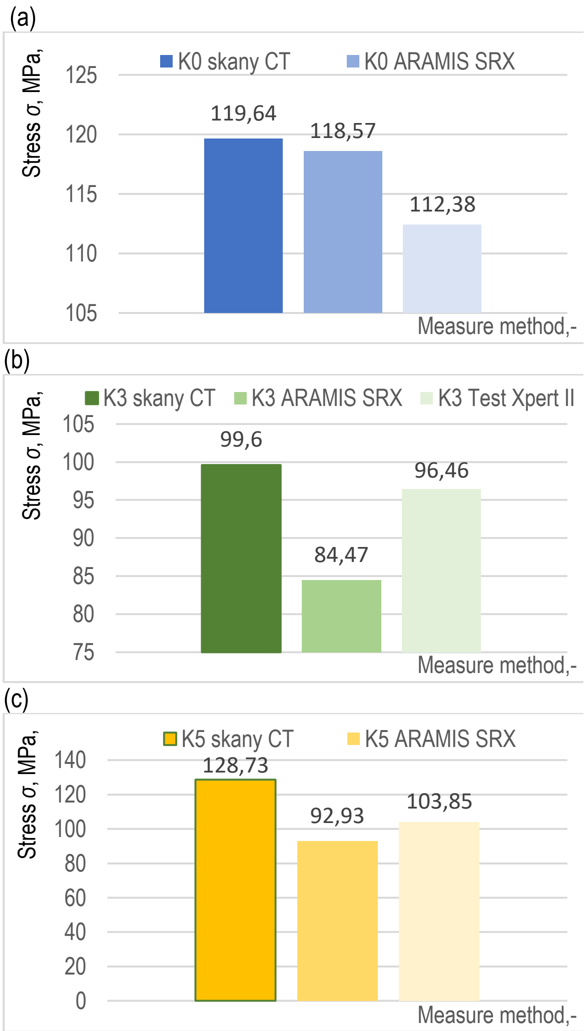


Fig. 20. Summary of differences in stress measurements in samples based on CT scans – after taking into account the recyclate in the cross-section



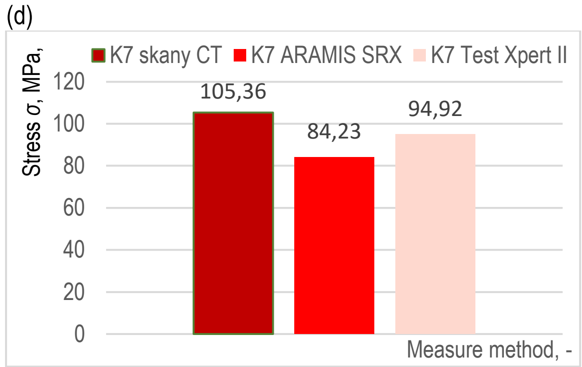


Fig. 21. Summary of the obtained tensile strength Rm values for the tested materials, taking into account the measurement method used for samples: a) K0; b) K3; c) K5; d) K7

Tab. 9. Tensile strength values obtained from ARAMIS SRX data and CT scans

Material	Rm, MPa **scans CT**	Rm, MPa **ARAMIS SRX**	**Percentage drop, %**
K0	119.64	118.57	–0.9
K3	99.6	84.47	–3.3
K5	128.73	92.93	–24.0
K7	105.36	84.23	–11.0

Analyses made in GOM Suite 2021 software, taking into account the cross-sectional areas of the measuring parts of the samples, were used to determine material properties such as Young modulus E. Bearing in mind that the modulus E is the quotient of stress and strain, it can be concluded that for the same longitudinal strains measured by the ARAMIS SRX system on the surface of the samples depending on the method of calculating the cross-section, a different value of the E modulus was obtained. After taking into account the voids in the sections caused by the presence of rubber recyclate grains, these fields will be smaller. Reducing the cross-sectional area of the measuring part affects the value of the Young modulus E determined for each sample. Tab. 10 presents the differences in the values of the Young modulus for the tested variants of materials obtained as a result of verifying the values of the cross-sectional areas of the measuring parts of the samples, after analysing the CT scans.

Tab. 10. Young modulus values of K0, K3, K5 and K7 composites determined from the ZwickRoell machine and by using the ARAMIS SRX system and by using CT scans

Material	Young modulus *E*, MPa		
	Data obtained from TestXpert II software of the ZwickRoell testing machine	Data from the ARAMIS SRX system, based on external measurements of the sample geometry	Data obtained from CT scans, after accounting for voids in the cross-sections of the samples
K0	7,930	8,467	8,391
K3	5,978	8,032	6,812
K5	6,632	9,813	7,084
K7	5,874	8,236	6,584

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The differences in Young modulus values for the tested variants of composite materials determined based on ARAMIS imaging and CT scans are significant. For the K0 variant, the discrepancy of the obtained *E* modulus values is almost 536 MPa, while for the K5 variant, this discrepancy is 3181 MPa. Such significant differences in measurements indicate a significant need to use modern measurement techniques to determine new composites' material constants. This is of particular importance when there are voids in the cross-section of the tested material, such as those caused by the presence of rubber recyclate grains in composite materials. The type of composite construction affects the strength properties, and taking into account voids in cross-sections is possible only after using the CT scanning technique; it makes allows predicting what load the tested material can take. After determining the actual cross-sectional areas of the tested samples, it turned out that the value of these loads must be lower than that would result from the parameters determined during the static tensile test without the use of optical measuring techniques.

4.4. Analysis of the course of deformations in the tested composite materials

During the tests, an analysis of the process of deformation in the samples during the static tensile test was performed for each of the analysed variants of the material. As the measurement threshold defines the occurrence of deformation that leads to the cracking of the sample, the value of 1.2% of the maximum deformation created in the sample during stretching was set. Such deformations were created in the sample and developed during the test until the material broke. An example of crack analysis carried out on the measuring length of the sample for samples K0 and K5 is shown in Figs 22–25.

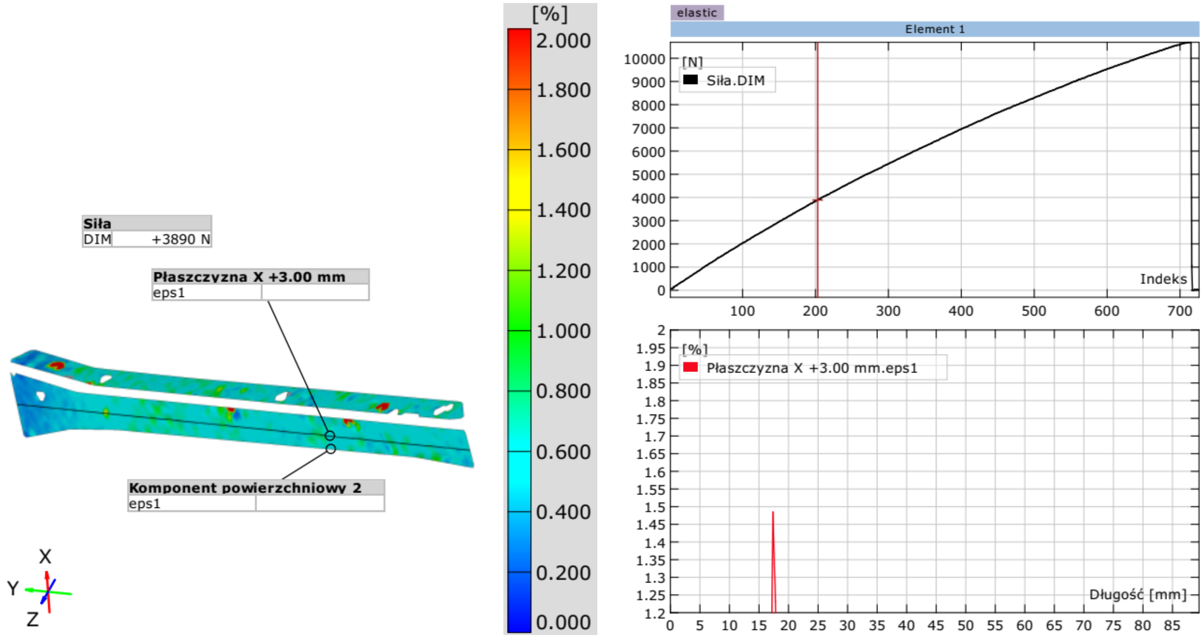

Fig. 22. Course of the main strains I in the longitudinal section of the K0 sample on the measuring part in the period of the first strains

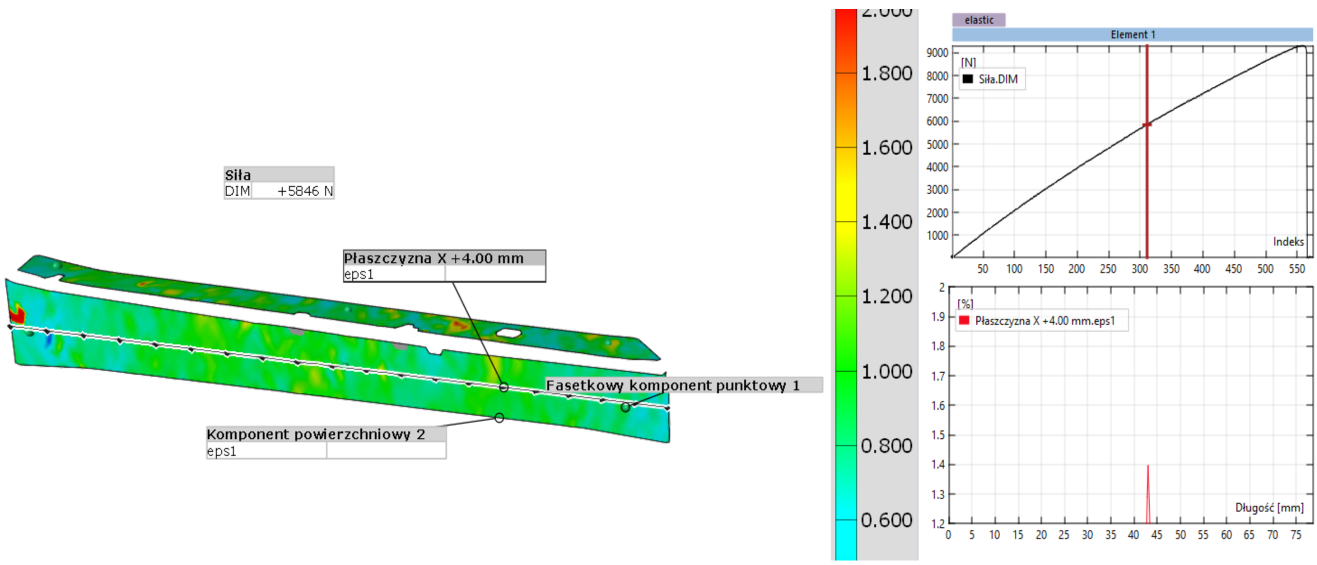

Fig. 23. Course of the main strains I in the longitudinal section of the K5 sample on the measuring part during the crack initiation period

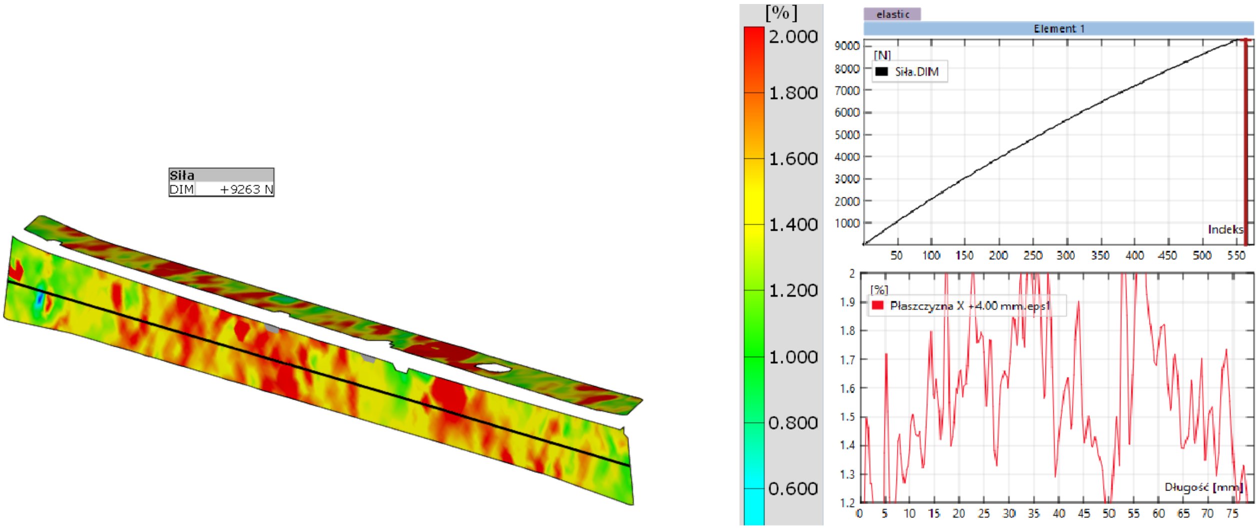

Fig. 24. Course of the main strains I in the longitudinal section of the K5 sample into parts in the period before the sample breaks

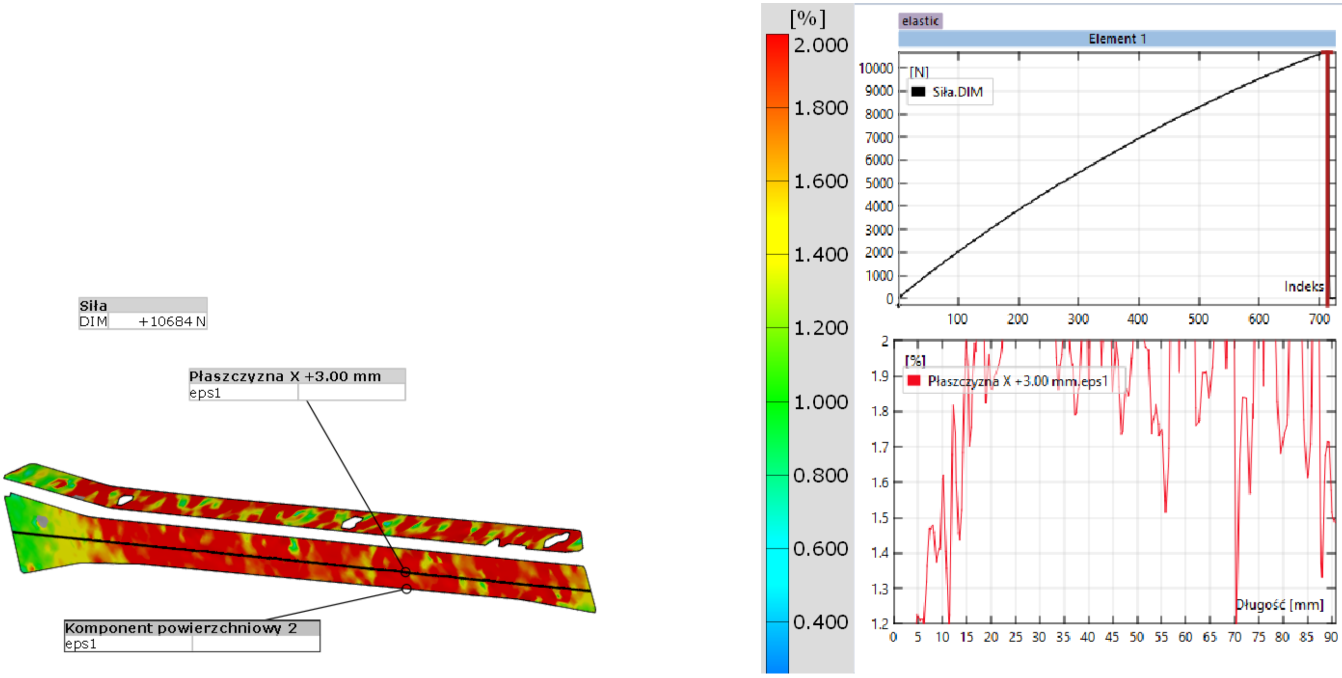

Fig. 25. Course of the main strains I in the longitudinal section of the K5 sample into parts in the period before the sample breaks

Tab. 11. Values of forces at which strains appear in the sample exceeding 1.2% of the maximum strains obtained in the sample during the static tensile test

Force / material			K0	K3	K5	K7
F [N]			3,890	7,251	7,846	7,826
σ [%] of σ_{MAX}	1.45	1.5	1.4	1.42		

The analysis of cracks in the tested samples confirms the beneficial effect of the rubber recyclate addition on the elastic properties of the tested composites. The addition of recyclate caused cracks in the samples to appear only after the tensile force was significantly exceeded in comparison with the pure composite. For the K0 sample, the value of the force beyond which deformations appear at the level of 1.2% propagating over time to the sample's fracture is about 3,890 N. For comparison, the value of this force for the K7 composite is already 7,826 N. The list of forces at which they appear in the sample strains at the level of 1.2% of the maximum strains propagating with time until the sample breaks are shown in Tab. 11.

5. SUMMARY

The analysis of the obtained results showed that the addition of rubber recyclate to the resin reduces the strength parameters of the epoxy–glass composite in terms of percentage elongation, Young modulus and tensile strength. However, it is worth noting the beneficial effect of the rubber recyclate addition on the elasticity, as well as the deformation method of the tested composite materials. For each of the material variants, the value of the Poisson number increased in comparison with the base material K0.

In the case of the analysis of material properties for a new composite material, it is important to precisely determine the parameters characterising the strength of the new material. The studies and analyses carried out have shown that the use of modern optical measurement systems creates new possibilities in the analysis of the properties of composite materials. Of particular importance are such measurements for newly developed composite materials with high anisotropy, for which it is difficult to use traditional computational models or numerical analyses based on FEM software. The article's authors used the ARAMIS system's capabilities and GOM Suite software to test the strength parameters of newly manufactured epoxy–glass composites with the addition of recyclate derived from non-degradable rubber substances. The production of a new construction material is the beginning of the road, the next stage of which is always the analysis of mechanical and physicochemical properties. These analyses lead to finding an area where the newly produced material can be used. Crack analysis in the variants of composite materials presented in this study confirms the beneficial effect of the addition of rubber recyclate on the elastic properties of the tested composites. The addition of recyclate caused cracks in the samples to appear only after the tensile force was significantly exceeded in comparison with the pure composite.

Important for the research is the noticeable effect of the percentage amount of the additive on the parameters of the new composite. The most promising composite turned out to be the variant containing a 5% random addition of rubber recyclate to the composite matrix. At the same time, the influence of the rubber recyclate addition on the actual tensile strength properties of the tested materials should be noted. The analysis of CT scans showed that the new material can transfer fewer loads than it would result from the data determined by traditional methods. Research has shown that it is beneficial to use additives from environmentally friendly recycling processes in new materials while improving their specific mechanical and functional parameters. For certain manufacturing applications, such a significant improvement in elasticity can be an important factor in choosing this variant of the solution. Ease of access to this raw material and its low cost of acquisition have a positive effect on the producer's favourable economic balance.

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