Research Article

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Investigation of the influence of recyclate content on Poisson number of composites

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Abstract: Composite materials are used in many industries. Their mechanical and physical properties as well as their low weight make them suitable for use in many constructions. Their wide application generates a problem with their disposal. Therefore, it is necessary to design new materials based on waste from polyester–glass laminates in order to introduce a closed circuit in the composite production process. The article presents research aimed at determining solid material composites with polyester–glass recyclate, in order to use these materials for modeling the structure. The aim of this study was to determine the effect of the addition of recyclate to the polyester–glass composite on the deformation and the value of the Poisson number of the material. During the study, samples from composites with the addition of polyester–glass recyclate were used. Samples made in accordance with the standard for plastics PN-EN ISO 527-4_2000P were subjected to static tensile test on a universal testing machine, with variable load parameters. During the test, the longitudinal and transverse elongations of the samples were measured using a strain gauge measuring system. On the basis of the measurements, the values of Poisson numbers were determined, which allowed for a preliminary assessment of the impact of the recyclate content in the composite on its deformability.

Keywords: polyester–glass composites, electrofusion strain gauge, strain gauge measurements, Poisson number, static tensile test

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1 Introduction

Over the last few years, there has been a significant increase in the use of composite materials, in particular those with fiberglass reinforcement. The interest in this material is related to relatively high mechanical and physical properties, low weight and the ease of forming various types of shapes. They are used as a construction material in industry, from the main construction material of vessels in the yachting industry, to railways, automotive and aviation [1–4]. The wide range of use of these materials translates into the amount of waste, which makes it necessary to develop methods of their utilization [5,6]. There are many methods for recovering glass fibers from waste and it is possible to use them as full-value components [7], replacing part of the reinforcing phase in the new materials [8–10]. The recycling of composite materials is a topic of global importance and continues to be a scientific goal of research teams around the world. The material that was previously considered unusable turns out to be usable, thus contributing to waste management [2,11,12]. The potential for saving resources through the use of more sustainable and advanced composites production methods is visible [13,14].

Earlier studies have shown that the use of polyester–glass recyclate as a filler in the matrix of new composite materials is a future-oriented and innovative direction in terms of polyester–glass waste recycling [15]. The use of polyester–glass recyclate reduces the mechanical properties of the composite material; however, the material can still be used for less responsible constructions, such as superstructures [3]. It is also possible to produce composite materials with a filler in the form of polyester–glass recyclate, not only by hand lamination [16] but also by the vacuum bag method [15]. These are materials which can be shaped in any direction, which additionally makes them more attractive, but hinders the design process [17,18]. Therefore, it seems necessary in terms of the use of these materials to determine the solid materials necessary for modeling various types of structures [19–32]. This could contribute to the industrial application of these materials.

In this article, composite materials with polyester–glass recyclate were used to determine the Poisson's ratio. The determination of this parameter is significant not only in terms of determining the deformability of this material, but also in terms of modeling. A static tensile test was carried out in order to determine the Young's modulus. In addition, tests were carried out with the use of strain gauges, measuring the longitudinal and transverse elongations to determine the Poisson's ratio. On the basis of the performed measurements, the values of Poisson numbers were determined, which allowed for a preliminary assessment of the impact of the recyclate content in the composite on its deformability.

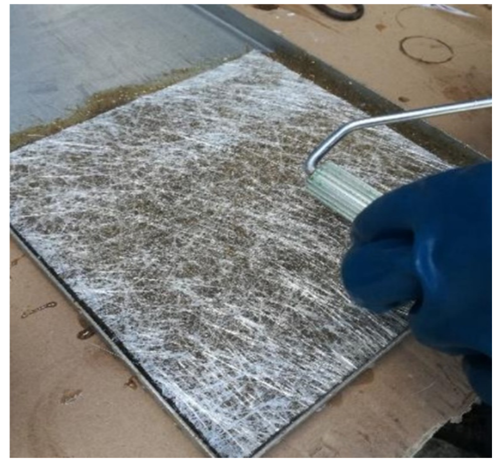


Figure 2: Manual production of polyester–glass composite.

2 Materials and methods

The tests were carried out on samples made of polyester–glass composites. The composites contained various contents of recyclate and were made by hand lamination. The method of preparing composites with different recyclate content is described in detail in refs. [6–8]. Three composite samples were prepared for the study with the content of polyester–glass recyclate in the amount of 10 and 20%, and for comparison purpose, a composite sample without recyclate was also used. The recyclate granulation was <1.2 mm.

The recycle material was part of the hull of a decommissioned and scrapped vessel. Composite scrap obtained from the fuselage elements was initially crushed with a hammer and processed into polyester–glass granules using a crusher (Figure 1). After the process, the granulate was screened through sieves with a mesh diameter ≤1.2 mm.

In the next stage of composite preparation, materials were formed with the use of recyclate. The production of polyester–glass laminates with the addition of recyclate was carried out using the manual laminating method [9,10] with the use of metal molds, glass mat, recyclate and polyester resin and a roller for even distribution and saturation of excess resin (Figure 2). Polimal 1094-AWTP resin was used. As a result of manual lamination, a research material was obtained with a specific number of glass mat layers and the assumed percentage composition of resin and recyclate [11,12] (Table 1).

Test specimens were made from composite materials prepared in this way. The samples were made by the water cutting method, and their shape and dimensions were consistent with the standard of static stretching of composite materials PN-EN ISO 527-4_2000P (Figure 3) [14].

Figure 4a shows the view of samples made of polyester–glass composite without recyclate – K0. Figure 4b

a) b)

Figure 1: (a) Crusher – a stand for processing composite materials and (b) view of polyester–glass granules with the grain size ≤ 1.2 mm [6,8].

Table 1: Percentage composition of composite materials used in the research [6,8]

Composite marking	Recycle content (%)	Glass mat content (%)	Resin content (%)	Number of layers of glass mat	Glass mat (g)	Resin (g)	Recycle (g)
K0	0	40	60	12	192.1	288	—
K10	10	30	60	10	169.7	339	56.5
K20	20	25	57	10	165.0	366	117

shows a photo of the surface structure of the samples taken with the LEXT OLS41000 confocal laser microscope. In Figure 4b, air pores and resin particles are noticeable, especially at the reinforcement.

An important aspect is the adhesion between the resin and the fibers. Moreover, the boundary between the fibers is visible.

The surface structure of samples with 10% recyclate content (Figure 5a and b) is characterized by a large number of pores; moreover, recyclate granules in the structure are visible. There is a noticeable reduction in adhesion between the resin with recyclate and the reinforcement. The influence of the recyclate on the structure is observed between successive layers of reinforcement.

Figure 6a shows the view of samples made of polyester–glass composite with a 20% content of recyclate – K20. Due to the higher content of recyclate, dark color of the samples is observed. In Figure 6b, large recyclate inclusions and air pores are noticeable. Moreover, the boundary between the fibers is visible.

In the generalized Hooke's law, expressing the relationship between the state of deformation and stress, there is a compliance matrix containing two material constants for isotropic bodies (E, ν). However, in the case under consideration, for monotropic (transversally isotropic) bodies, there are five material constants [1–5].

According to refs. [1,2,4], for material with orthogonal anisotropy, the generalized Hooke's law written in the summation convention is expressed as:

$$\varepsilon_j = S_{jk}\sigma_k, \tag{1}$$

where $[S_{jk}]$ – material compliance matrix j, k = 1, 2,...,6 (j – the direction of stress and k – the direction of the corresponding deformation).

In the literature of the description of composite properties, the index notation 1, 2, 3 is used, corresponding to the coordinate axis system (Figure 7).

In the general case, for an orthotropic material, the components of the compliance tensor using engineering constants in the form of matrices can be written [17]:

$$S = \begin{bmatrix} \frac{1}{E_1} & -\frac{\nu_{21}}{E_2} & -\frac{\nu_{31}}{E_3} & 0 & 0 & 0 \\ -\frac{\nu_{12}}{E_1} & \frac{1}{E_2} & -\frac{\nu_{32}}{E_3} & 0 & 0 & 0 \\ -\frac{\nu_{13}}{E_1} & -\frac{\nu_{23}}{E_2} & \frac{1}{E_3} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{32}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{13}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}} \end{bmatrix}. \tag{2}$$

There are 12 terms other than zero in the susceptibility matrix (2). Due to their symmetry with respect to the main diagonal, relations take place:

$$S_{jk} = S_{kj}, \quad \text{where } (k,\ j = 1,2,\ldots,6) \text{ or}$$
$$\frac{\nu_{\mathrm{lh}}}{E_{\mathrm{l}}} = \frac{\nu_{\mathrm{hl}}}{E_{\mathrm{h}}}, \text{ where } (h, l = 1, 2, 3),$$

and on this basis the number of independent terms of the susceptibility matrix is reduced to 9.

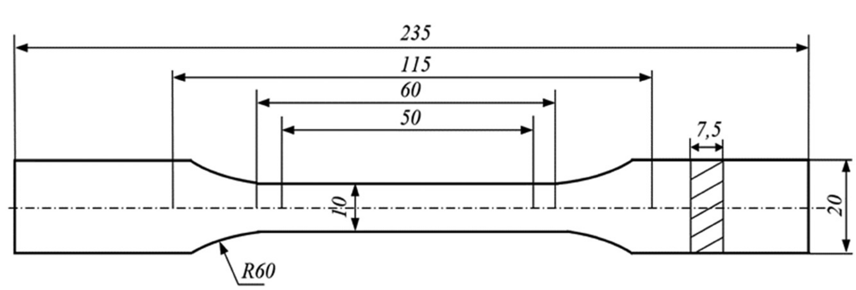
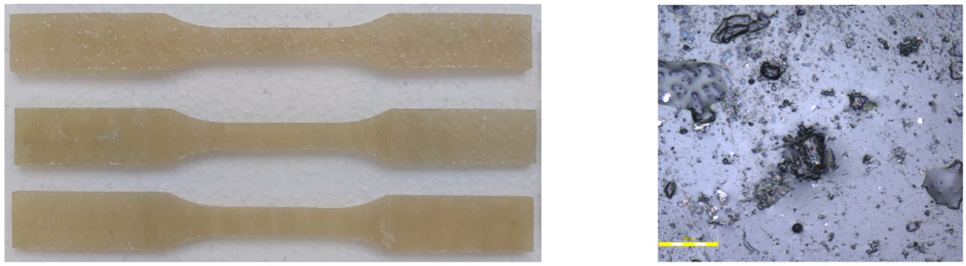


Figure 3: Shape and dimensions of test samples.

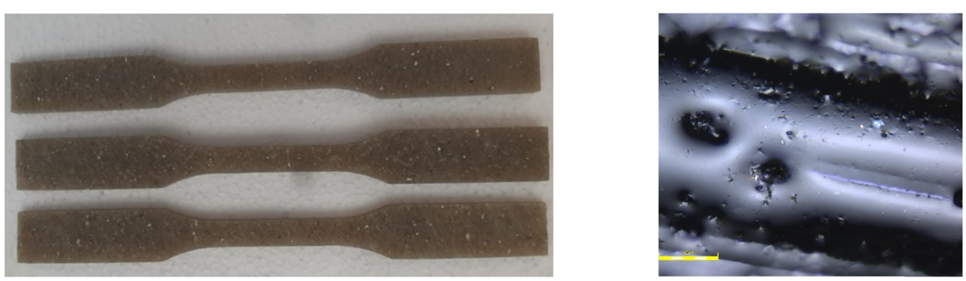


(a) (b)

Figure 4: View of samples without the addition of recyclate (a) and structure of the K0 composite at magnification 50× (b).

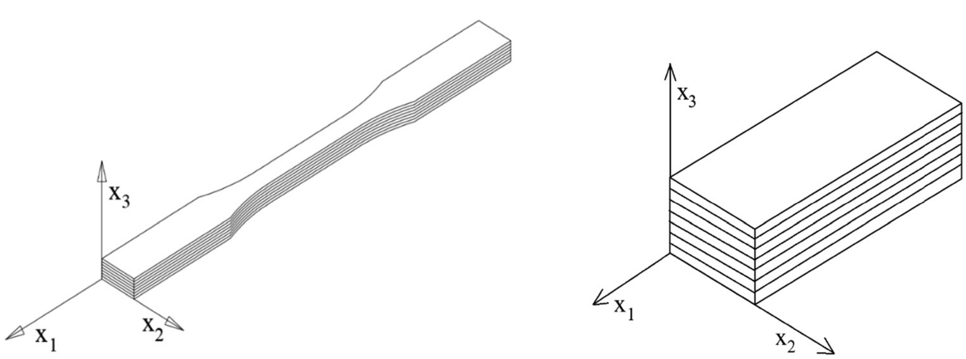
a) b)

Figure 5: View of samples with 10% recyclate content (a) and structure of the K10 composite at magnification 50× (b).



a) b)

Figure 6: View of samples with 20% recyclate content (a) and K20 composite structure at magnification 50× (b).



a) b)

Figure 7: Orientation in the coordinate system (a) and the measuring part of the sample (b).

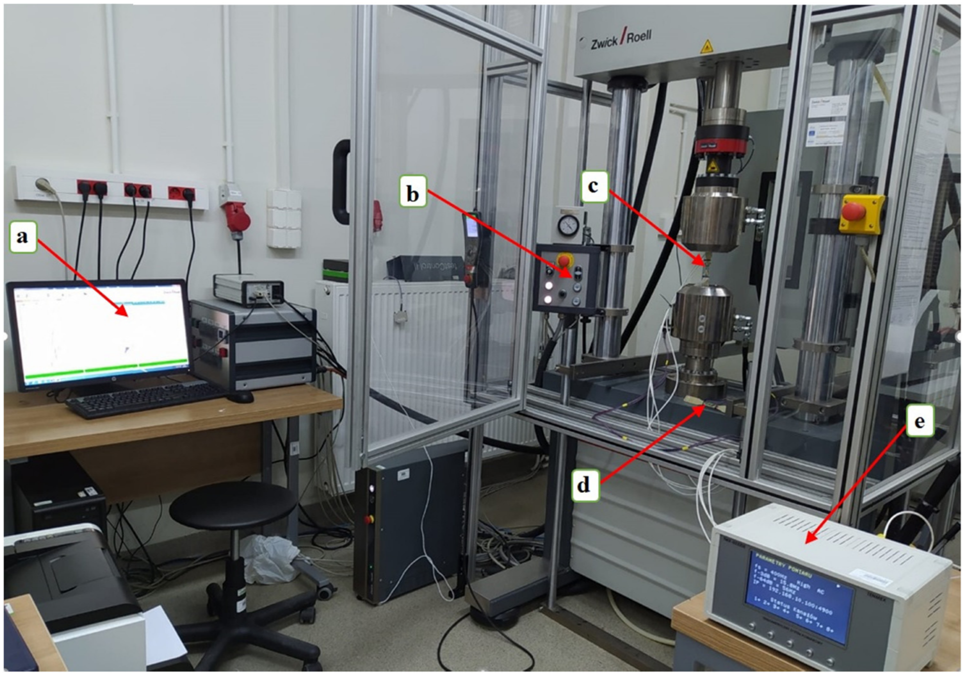


Figure 8: View of the Zwick Roell testing machine during the test. Computer stand (a), control panel of the machine (b), fixed composite sample (c), temperature compensation sample (d) and strain gauge measuring system (e).

On the other hand, for a monotropic material, on the basis of the tensor transformation law, it is proved during rotation that additional equality takes place. If the axis of symmetry is axis 3 (Figure 7), then:

$$E_1 = E_2, E_3, \frac{\nu_{21}}{E_2} = \frac{\nu_{12}}{E_1}, \frac{\nu_{31}}{E_3} = \frac{\nu_{13}}{E_1}, \frac{\nu_{32}}{E_3} = \frac{\nu_{23}}{E_2}, \quad (3)$$

the fifth constant results from mutual relations.

The tested composite materials are monotropic materials. The value of the Poisson number for each of the tested samples was defined as the ratio of the transverse to longitudinal deformation [1,2,4] in accordance with the strain gauge markings in Figure 10 [15,16].

$$-\nu_{12} = \frac{\varepsilon_2}{\varepsilon_1} = \frac{\varepsilon_{T1}}{\varepsilon_{T3}}, \quad (4)$$

$$-\nu_{13} = \frac{\varepsilon_3}{\varepsilon_1} = \frac{\varepsilon_{T4}}{\varepsilon_{T2}}, \quad (5)$$

where ε_2 – value of deformations measured with a strain gauge $T1$ on the end face, where

$$\varepsilon_{T1} = \varepsilon_2,$$

ε_1 – value of deformations measured with the strain gauge $T3$ on the face surface and with the strain gauge $T2$ on the lateral surface, where

$$\varepsilon_{T3} = \varepsilon_{T2} = \varepsilon_1,$$

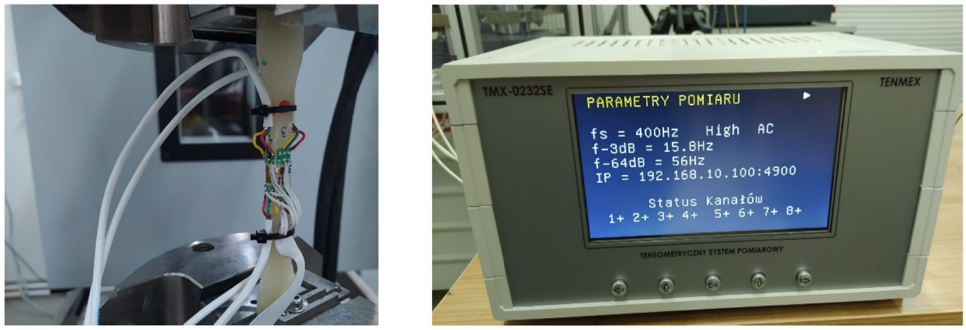
ε_3 – value of deformation measured with a strain gauge $T4$ on the side surface of the sample, where

$$\varepsilon_{T4} = \varepsilon_3.$$

Tensometric tests were carried out on samples subjected to tension using a universal Zwick Roell testing machine with a hydraulic drive, type MPMD P10B with TestXpert II software, version 3.61 (Figure 8). The test results for the samples were recorded using ZwickRoell-TestXpert II version 3.61.

To measure the deformation of the samples, a strain gauge TMX 0216SE measuring system (TENMEX, Poland) was used (Figure 9b), designed to work with strain gauges, in particular with strain gauges glued on the front and side surfaces of the sample (Figure 9a). In order to precisely place the strain gauge in a specific place on the sample, the cyanoacrylate adhesive TB-1731 and the self-adhesive TT-18 tape recommended by the manufacturer of the foil strain gauges were used [13].

Tensometric tests were carried out on samples subjected to stretching with a force of 100, 200, 300 and 400 N, with automatic registration of deformations using strain gauges. The use of the TMX 0216SE multi-channel strain gauge bridge made it possible to measure the longitudinal and transverse deformations of the samples of the tested materials. The deformation of the samples for each load value (100, 200, 300 and 400 N) was recorded after a fixed time interval for the given load. A diagram of the place of sticking strain gauges on the working part of samples oriented in the Cartesian coordinate system is shown in Figure 10.



a) b)

Figure 9: Sample with glued resistance strain gauges (a) and TMX 0216SE strain gauge measuring system (b).

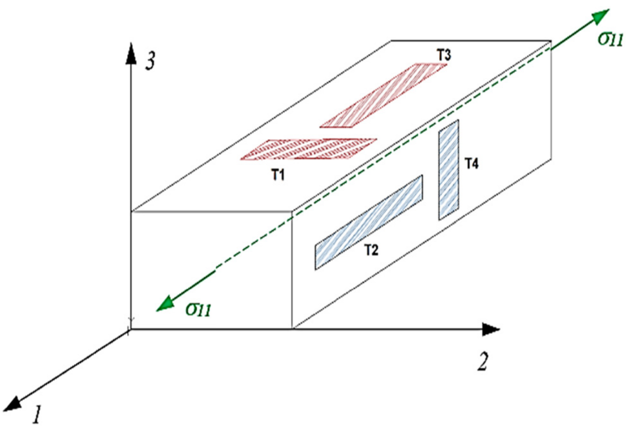


Figure 10: Arrangement of strain gauges on the sample measuring surfaces.

3 Results and discussion

Based on the studies [8,9], the values of Young's modulus were obtained, which are listed in Table 2.

The results of strain gauge tests of the tested polymer composites without recyclate and with recyclate in accordance with the designations of strain gauges in Figure 10 are presented in Tables 3–5.

Using the compounds (3), the Poisson's ratio values of the tested composites with and without recyclate were determined in accordance with the markings in Figure 10.

Table 2: Values of Young's modulus of samples from composite with the addition of recyclate with a granule size ≤1.2 mm produced by the manual laminating method

Composite	$E_1 = E_2$ (MPa)	E_3 (MPa)
K0 – 0%	7,004	3,650
K10 – 10%	5,682	2,850
K20 – 20%	5,318	2,570

Table 3: Results of strain gauge measurements of samples K0 without recyclate

F (N)	$\varepsilon_{T3} = \varepsilon_{T2} = \varepsilon_1$	$\varepsilon_{T1} = \varepsilon_2$	$\varepsilon_{T4} = \varepsilon_3$	Time (s)
100	56.3	−18.5	−12.9	30
200	124.6	−42.6	−27.7	30
300	194.5	−64.7	−45.7	30
400	259.2	−85.8	−63.8	30

Table 4: Results of strain gauge measurement of composite samples K10 with 10% recyclate content

F (N)	$\varepsilon_{T3} = \varepsilon_{T2} = \varepsilon_1$	$\varepsilon_{T1} = \varepsilon_2$	$\varepsilon_{T4} = \varepsilon_3$	Time (s)
100	139.1	−47.7	−33.4	30
200	195.2	−68.3	−46.8	30
300	297.5	−108.1	77.4	30
400	414.0	−141.9	−103.5	30

Table 5: Results of strain gauge measurement of samples K20 with 20% recyclate content

F (N)	$\varepsilon_{T3} = \varepsilon_{T2} = \varepsilon_1$	$\varepsilon_{T1} = \varepsilon_2$	$\varepsilon_{T4} = \varepsilon_3$	Time (s)
100	229.7	−80.7	−64.3	30
200	480.5	−178.0	−120.1	30
300	822.4	−297.1	−213.8	30
400	1063.0	−379.7	−308.3	30

Table 6: Values of Poisson's ratios for composites K0, K10 and K20

Composite	$\nu_{12} = \nu_{21}$	$\nu_{13} = \nu_{23}$	$\nu_{31} = \nu_{32}$
K0	0.33	0.23	0.12
K10	0.35	0.25	0.12
K20	0.36	0.27	0.13

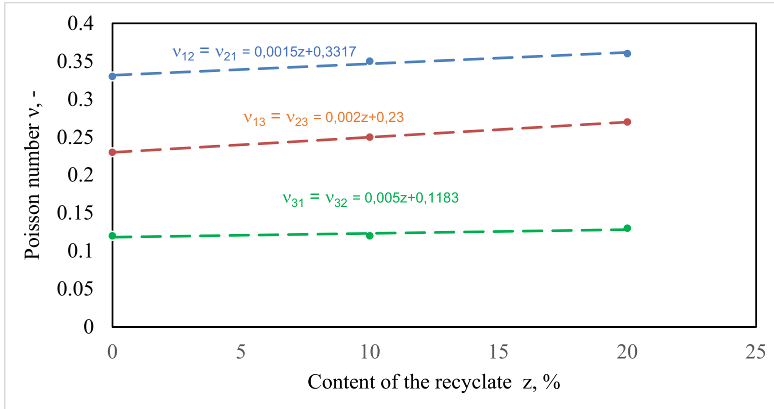


Figure 11: Diagram of dependency between Poisson number and content of the recyclate in samples.

$$\frac{\nu_{12}}{E_2} = \frac{\nu_{21}}{E_1}, \text{ using equation and dependency,} \quad (4)$$

because $E_1 = E_2$, so $\nu_{12} = \nu_{21}$, $-\nu_{12} = \frac{\varepsilon_2}{\varepsilon_1} = \frac{\varepsilon_{T1}}{\varepsilon_{T3}}$

$$\frac{\nu_{31}}{E_3} = \frac{\nu_{13}}{E_1}, \text{ using equation and dependency,} \quad (5)$$

$$\frac{\nu_{32}}{E_3} = \frac{\nu_{23}}{E_2},$$

because $\nu_{13} = \nu_{23}$ and $\nu_{31} = \nu_{32}$ so

$$-\nu_{13} = \frac{\varepsilon_3}{\varepsilon_1} = \frac{\varepsilon_{T4}}{\varepsilon_{T2}},$$

$$\nu_{31} = \nu_{13}\frac{E_3}{E_1}.$$

The average values of Poisson's ratios for the composite without K0 recyclate and with K10 and K20 recyclates are shown in Table 6.

Figure 11 shows the changes in the value of the Poisson's ratio depending on the content of the recyclate in the polyester–glass composite.

The changes in the values of Poisson's ratios depending on the content of recyclate in the polyester–glass composite presented in Figure 11 prove the changes in the mechanical properties of the tested composites. The increase in the content of recyclate caused a decrease in the value of Young's modulus and an increase in the value of Poisson's coefficients. Composites with a higher content of recyclate show an increase in the deformability of the material with a decrease in mechanical properties.

4 Conclusion

Determining the physical properties of polyester–glass composites with the addition of recyclate requires conducting experimental and analytical research. Tensometric tests allow to determine material constants, i.e., Poisson coefficients, with high accuracy.

The tests carried out with the use of strain gauges showed that changes in the percentage of recyclate content in the composite have a significant impact on the change in the strength properties, i.e., longitudinal and transverse deformations, and, as a result, on the change in the Poisson's ratio. The measurement results became the basis for determining the trend of changes in the Poisson's ratio depending on the changes in the recyclate (10 and 20%) in the composite.

The increase in the content of recyclate from 0 to 20% resulted in an increase in the deformability of the material and a reduction in its mechanical properties.

Determining the detailed changes in the composite deformability in relation to changes in the percentage of recyclate content requires the preparation and testing of a larger number of samples with a smaller jump in the percentage changes of the recyclate content.

Conflict of interest: Authors state no conflict of interest.

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