Composite Materials with Epoxy Matrix and Their Properties

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Abstract. This work was focused on studying the properties of epoxy (EP) composite materials reinforced with glass, (GF) carbon (CF) and aramid (AF) fibres. The composites were made by hand lay-up (HL) and vacuum infusion process (VIP) with 8, 10, 12 number of fabric layers. Studied were tensile strength, elongation, flexural stress, flexural strain, thermal stability, texture of surfaces, cuts, fractures of laminates and the thickness of the laminate according to the type and number of fabric and the method of manufacture. Composites made by VIP achieve better mechanical properties than composites made by HL. Tensile strength was highest in composites reinforced with AF. Composite materials reinforced with GF exhibit the lowest values of tensile strength. Flexural strength was significantly the highest in CF reinforced composites followed by the laminates reinforced with GF and AF. The highest values of flexural deformation were measured in composites reinforced with AF and the lowest values of flexural deformation were measured in composites reinforced with CF. By thermogravimetric analysis (TG) was recorded weight loss of the EP matrix in the range from 290 to 480 °C and AF in range from 530 to 605 °C. By TG was demonstrated lower content of EP matrix in the composites made by VIP, which was confirmed by comparison of thickness of the studied laminates.

1. Introduction

Most synthetic polymers are produced in chemical factories from where they are subsequently supplied by the manufacturer of plastic products where the final plastic products are produced by shaping, mixing, extrusion or pressing. However, these processes required to produce the final product are purely physical and do not require substantially any chemical reaction of the polymers. Since most polymers are immiscible, there is not much room to modify the properties of polymers in the production of plastics. For this reason, in most cases, the properties of the final product are modified by the use of different additives \textsuperscript{[1]}. Some of the polymers, commonly called resins, are supplied to the chemical industry as precursors. Here, a chemical reaction is required to produce the final product. The treatment of polymers is particularly advantageous if only relatively small changes in certain properties are required, which cannot be achieved directly in chemical plants. Due to the fact that a large number of precursors can be combined in the production of the final resin, the variability and the ability to influence the final properties of the material are much higher compared to the rest of the polymers \textsuperscript{[1]}. Epoxy polymers are very widespread materials today, mainly due to their use in composite materials as matrix. In general,
they have high specific strength and hardness, high chemical resistance, good processability, are resistant to weathering and are relatively inexpensive. Cured epoxides with an ordered three-dimensional network molecular structure are relatively thermally stable and have a relatively high glass transition temperature. However, they are very brittle and have very low resistance to crack propagation, which limits their general use in components. Therefore, if they are used in mechanically loaded components, it is necessary to reinforce them. In [2] they dealt with epoxies filled with polybutadiene rubber particles, which prolonged the polymerization duration and thus the gelation point. Impact and fracture toughness have been improved, as well as resistance to crack propagation. In [3], silica nanoparticles were used as reinforcement, which resulted in an increase in Young's modulus, a substantial increase in fracture toughness. In [4], the effect of adding this filler on the fatigue life of epoxy and glass fiber reinforced epoxy composite was investigated. Another attempt to improve the properties of epoxy composites was discussed in [5], where alumina nanoparticles and titanium dioxide nanoparticles were used as reinforcement. The addition of both fillers increased the flexural strength, flexural stiffness and fracture toughness. Alumina also increased the resistance to fatigue propagation of microcracks, yield strength and plastic deformation. Works [6] and [7] deal with the reinforcement of the epoxy matrix with carbon nanotubes. Both studies show a significant improvement in the mechanical properties of the material, such as strength, stiffness and in particular fracture toughness. In general, it can be evaluated that solid nanoparticles increase the toughness and stiffness of the material without losing the thermal properties of epoxies. Good interfacial adhesion between the filler and the matrix also ensures an increase in the plastic deformation of the material [7–9].

1.1 Fiber-reinforced epoxy composites

Epoxies are most often fiber reinforced. In practice, carbon, aramid, glass, polyphenylene sulfide, polybenzoxazole and high-density polyethylene fibers are the most widely used [10–12]. The work [10] is focused on the study of tensile and bending properties of epoxy composites reinforced with carbon, aramid and glass fibers and various combinations of these reinforcements. It is clear from the tensile curves that the best tensile strength was achieved by composites in which carbon fibers were present. The arrangement of the layers of individual types of fabric also has a significant effect on the strength and stiffness. Carbon fiber composites have many excellent properties but have relatively low impact resistance. This problem is solved in [13] by replacing several layers of carbon fibers with aramid. It is well known that few materials match the aramid composite in impact strength. However, this type of fiber is relatively expensive. The mechanical properties of the fiber-reinforced composites are also influenced by the method of knitting the fibers, as proved in the work [14]. Hybrid polypropylene glass fibers in combination with a thermoplastic epoxy matrix were used for this research. Seven types of knitwear were compared. The study shows that the type of knit, and the correct direction of stress can increase the tensile strength up to ten times, increase the modulus of elasticity five times, increase the flexural strength six times and increase the impact strength of the composite up to eight times.

1.2 Production of fiber-reinforced epoxy composites

There are two basic types of manufacturing processes for fiber-reinforced polymer matrix composites. In the first, the fiber or fabric is first formed into the desired shape and only then is impregnated with resin. The second procedure is the production of the so-called prepregs, which is a layer of unidirectional or woven fibers impregnated with a thermoplastic or thermosetting resin, which is then formed into the desired shape and subsequently cured. Another technology for the production of fibrous composites is cold pressing. It is performed by applying low pressure at normal temperature [15]. The most expensive and complex technology used for series production is autoclave pressing. Only prepregs requiring curing at elevated temperatures are processed by this method [15]. Another method by which fiber-reinforced polymer composites are produced is hot and pressure molding. In this way, either prepreg molding compounds (SMCs) and dough molding compounds (DMCs) or bulk molding compounds (BMCs) are processed [15]. Another type of technology are the so-called closed technologies that limit the evaporation of harmful gases during the processing and curing process. All modifications of these technologies are based on injection or infusion supersaturation of the dry reinforcement placed in the mold. The most used type of such technology is high pressure resin injection molding (RTM).
A modification of this technology is the injection of resin assisted by vacuum (VARTM - vacuum assisted resin transfer molding, RTM light). Vacuum infusion process (VIP) is also a commonly used technology. This method is very similar to vacuum compression [15]. Centrifugal casting is also used among the technologies used for the production of fiber-reinforced composites.

2. Experimental part

2.1 Materials

**Epoxy system used on hand lay-up (HL) [16]:** Biresin® CR82 (A) - epoxy resin for manual supersaturation, pultrusion and winding technology, viscosity (25 °C): 1600 mPa.s, density (25 °C): 1.11 g.ml⁻¹ (Sika, Germany). Biresin® CH80-2 (B) - amine crosslinker, viscosity (25 °C): 50 mPa.s, density (25 °C): 0.99 g.ml⁻¹ (Sika, Germany).

**Epoxy system used on vacuum infusion process (VIP) [17]:** Biresin® CR83 (A) - epoxy resin for infusion and injection supersaturation technologies, viscosity (25 °C): 510 mPa.s, density (25 °C): 1.14 g.ml⁻¹ (Sika, Germany). Biresin® CH83-2 (B) - amine crosslinker, viscosity (25 °C): <10 mPa.s, density (25 °C): 0.94 g.ml⁻¹ (Sika, Germany).

**Type of reinforcement:**
- Glass fabric 163 g.m⁻², AEROGLASS Kepr 2/2, Basic weight 160 ± 10 g.m⁻², material EC9 68 tex / EC9 68 tex,
- Carbon fabric CC 160 T – 120, Basic weight 160 ± 10 g.m⁻², material Toray 3K 200 tex/Toray 3K 200 tex,
- Aramid fabric 173 g.m⁻² – kepr 2/2, Basic weight 170 g.m⁻², material Aramid 1210 dtex/Aramid 1210 dtex.

2.2. Methods

**Preparation of composite materials**

Composite materials were made in two ways. In both production methods, an LB 60 pump from IKS Wien was used for descaling the resin mixture. In the vacuum production method (VIP), an LC 60 pump from IKS Wien was used to supersaturate the fiber reinforcement. The VENTICELL tempering furnace from the BMT Brno company was used for additional tempering of the produced composite materials. After tempering, the produced laminate sheets were cut to the required dimensions with an NAREX EBU 125-11 angle grinder. Composition of fiber-reinforced epoxy composites is in Table 1.

**Mechanical properties**

Measurements of the mechanical properties, such as tensile strength, elongation, flexural stress, flexural strain, were performed by the HOUNDSFIELD H20K-W, at 10 mm.min⁻¹ crosshead speeds during tensile tests and 2 mm.min⁻¹ during bending tests. Five measurements of each sample were realized, the average values obtained being reported in Figures 1–6. The maximum percentage error did not exceed 6.13 %.

**Advanced technique**

Observation of fracture surfaces, cross-sections and surfaces of composite materials were analyzed using the TESCAN VEGA3 Scanning Electron Microscope. All images are taken in secondary electron mode and provide micro-views of the surface of the samples to be examined. The prepared samples were plated with a fine layer of Au-Pd and placed in a microscope chamber.

**TG measurements**

Thermal stability of composite materials was analyzed by TG/DSC: TG/DSC 2 STAR® system, Mettler Toledo; dynamic heating from 30 to 1500 °C at 10 °C/min in N₂.
Table 1. Composition of fiber-reinforced epoxy composites.

| Type of composite | Epoxy matrix | Type of fibres | Number of layers of fabric | Method of preparation |
|-------------------|--------------|----------------|---------------------------|----------------------|
| EP/GF-8 (HL)      | Biresin® CR82 (A) + Biresin® C180-2 (B) | GF             | 8                         | HL                   |
| EP/GF-8 (VIP)     | Biresin® CR83 (A) + Biresin® C183-2 (B) | GF             | 8                         | VIP                  |
| EP/GF-10 (HL)     | Biresin® CR82 (A) + Biresin® C180-2 (B) | GF             | 10                        | HL                   |
| EP/GF-10 (VIP)    | Biresin® CR83 (A) + Biresin® C183-2 (B) | GF             | 10                        | VIP                  |
| EP/GF-12 (HL)     | Biresin® CR82 (A) + Biresin® C180-2 (B) | GF             | 12                        | HL                   |
| EP/GF-12 (VIP)    | Biresin® CR83 (A) + Biresin® C183-2 (B) | GF             | 12                        | VIP                  |
| EP/CF-8 (HL)      | Biresin® CR82 (A) + Biresin® C180-2 (B) | CF             | 8                         | HL                   |
| EP/CF-8 (VIP)     | Biresin® CR83 (A) + Biresin® C183-2 (B) | CF             | 8                         | VIP                  |
| EP/CF-10 (HL)     | Biresin® CR82 (A) + Biresin® C180-2 (B) | CF             | 10                        | HL                   |
| EP/CF-10 (VIP)    | Biresin® CR83 (A) + Biresin® C183-2 (B) | CF             | 10                        | VIP                  |
| EP/CF-12 (HL)     | Biresin® CR82 (A) + Biresin® C180-2 (B) | CF             | 12                        | HL                   |
| EP/CF-12 (VIP)    | Biresin® CR83 (A) + Biresin® C183-2 (B) | CF             | 12                        | VIP                  |
| EP/AF-8 (HL)      | Biresin® CR82 (A) + Biresin® C180-2 (B) | AF             | 8                         | HL                   |
| EP/AF-8 (VIP)     | Biresin® CR83 (A) + Biresin® C183-2 (B) | AF             | 8                         | VIP                  |
| EP/AF-10 (HL)     | Biresin® CR82 (A) + Biresin® C180-2 (B) | AF             | 10                        | HL                   |
| EP/AF-10 (VIP)    | Biresin® CR83 (A) + Biresin® C183-2 (B) | AF             | 10                        | VIP                  |
| EP/AF-12 (HL)     | Biresin® CR82 (A) + Biresin® C180-2 (B) | AF             | 12                        | HL                   |

3. Results and Discussion

3.1. Mechanical properties of fiber-reinforced epoxy composites

Mechanical properties such as tensile strength, relative elongation at break, flexural strength, flexural stress at failure, deformation at maximum stress and deformation at failure were studied on prepared samples of composite materials, thermal stability of composites by TG and surface morphology were investigated, cuts and fracture surfaces of the studied laminates. Tensile test results for EP/GF (HL), EP/GF (VIP), EP/CF (HL), EP/CF (VIP), EP/AF (HL) and EP/GF (VIP) composites are given of Figures 1 and 2.

From Figure 1, it can be seen that for all types and numbers of fiber reinforcement layers, higher tensile strength values were recorded for the samples made by VIP than for the samples made by HL. This was probably due to the lower content of EP matrix in the material, which was also confirmed by TG (Figures 7, 8) and the comparison of thicknesses of the studied composites (Figure 13). The higher tensile strength of EP composites produced by VIP could also be caused by a lower content of internal material defects in the form of air bubbles clogged during production, which is confirmed by SEM images of cross sections and fracture surfaces of studied materials (Figures 9–12). In Figure 1, it can be seen that in the case of samples made by VIP, the tensile strength increases slightly depending on the
number of layers of reinforcement. The highest values of tensile strength were recorded for composites reinforced with AF, which is probably due to very good tensile strength and toughness of aramid fibers as such and at the same time well-balanced interfacial adhesion between EP matrix and aramid reinforcement. The lowest value of tensile strength was recorded for the sample EP CF-12 (HL), which is probably due to the fact that it was made by hand and the largest number of air bubbles was introduced into it, which is confirmed by the fact that this sample was the coarsest from all studied laminates (Figure 13). From a comparison of EP/GF (VIP) and EP/CF (VIP) samples, it is clear that CF-reinforced composites have higher tensile strength values than GF-reinforced composites.

![Figure 1](image1.png)

**Figure 1.** Tensile strength of EP/GF, EP/CF and EP/AF composites produced by HL and VIP on the number of reinforcement layers.

![Figure 2](image2.png)

**Figure 2.** Elongation at break of EP/GF, EP/CF and EP/AF composites produced by HL and VIP on the number of reinforcement layers.

In addition to the tensile strength, the elongation at break was also examined on the studied samples (Figure 2). The highest values were recorded for the samples reinforced with AF, which indicates that this type of fibers is characterized by the greatest flexibility among the types of fibrous reinforcement examined. This is also confirmed by SEM images of torn GF (Figure 10), CF (Figure 11), AF
In contrast, the lowest elongation at break was recorded for CF-reinforced specimens, indicating that EP/CF composites appear to be the most brittle of all the materials studied. This is also confirmed by SEM images of fracture surfaces of the studied composite materials (Figures 9–12). It can also be stated that the lowest values of the elongation at break for CF-reinforced composites are due to the higher interfacial adhesion between CF and EP than for EP/GF and EP/AF composites. This is probably influenced by the higher segmentation of the CF surface compared to the GF and AF surfaces (Figure 2). However, when comparing the elongation at break of EP/GF and EP/CF composite materials, it should be taken into account that the CF-reinforced specimens were significantly thicker (Figure 13) than the GF-reinforced specimens despite the same number of reinforcement layers and the same basis weight of both types of fabrics. A slight increase in elongation at break was observed for most samples with increasing number of layers. After comparing the investigated production methods, no uniform dependence in this direction is obvious.

![Figure 3. Flexural strength of EP/GF, EP/CF and EP/AF composites produced by HL and VIP on the number of reinforcement layers.](image)

In Figure 3 shows the dependence of the flexural strength of the studied materials on the number of layers of the fabric reinforcement used. It is clear that the highest flexural strength values were measured for EP/CF samples, which was probably due to the best adhesion of the EP matrix to the CF reinforcement and thus the best homogeneity of the material compared to other investigated composite materials. The flexural strength of EP/GF (HL), EP/GF (VIP), EP/AF (HL) and EP/AF (VIP) composites is in the range of 300 to 400 MPa, which are compared to the highest measured value in the EP/G sample, CF-12 (VIP) (592.849 MPa) values lower by 33 to 49 %. Slightly lower values were recorded for AF-reinforced samples than for GF-reinforced samples. For all samples made by VIP, it is possible to observe a slight increase in flexural strength with an increasing number of layers of reinforcement. For samples made by HL, the same dependence can be observed after comparing the samples reinforced with GF and AF.

From the comparison of flexural strengths of samples EP/CF-8 (HL), EP/CF-10 (HL) and EP/CF-12 (HL) no dependence is evident, which is again probably due to uneven production conditions in the manual method of production. When comparing the flexural strength of the samples depending on the method of production, it is visible that higher values were measured in samples made VIP, which is due to lower content of EP matrix in the material, as confirmed by TG (Figures 7 and 8) and comparison of thicknesses of studied composites (Figures 13).

In Figure 4 shows the dependence of the flexural stress at failure of the studied composite materials on the number of reinforcement layers. These values are very similar to the values of flexural strength (Figure 3). For GF-reinforced specimens, the values of flexural stress at failure are 4 to 13 % lower than
the values of flexural strength, which indicates a decrease in bending stress after reaching the maximum value of flexural stress at failure. In the case of CF-reinforced composites, the values of flexural strength and flexural stress at failure are identical, which means that the EP/CF composite can be described as a brittle material. This statement is confirmed by the study of SEM images of fracture surfaces of composites EP/CF-10 (HL) (Figure 11) and EP/CF-10 (VIP) (Figure 11) after tensile test. The values of flexural stress at failure of AF-reinforced composites are identical to the values of flexural strength in the manual production method, but in samples made for VIPs, as with EP / GF composites, a slight decrease in flexural stress was recorded after reaching its maximum (1 to 4 %). This fact is probably due to the higher content of brittle EP matrix in the samples produced by HL, which was also confirmed by TG (Figures 7 and 8) and the comparison of the thicknesses of the studied laminates (Figure 13).

![Diagram of flexural stress at failure of EP/GF, EP/CF, and EP/AF composites produced by HL and VIP on the number of reinforcement layers.](image)

**Figure 4.** Flexural stress at failure of EP/GF, EP/CF, and EP/AF composites produced by HL and VIP on the number of reinforcement layers.

Dependence of deformation at maximum stress of the EP/GF, EP/CF, and EP/AF composites produced by HL and VIP from the number of reinforcement layers is shown in Figure 5. Highest values of deformation at max. stress were recorded for AF-reinforced samples. The lowest values of deformation at maximum stress had EP/CF composites. From the comparison of deformation at maximum stress, depending on the production method used, it is obvious that for all types of samples except EP/GF-10 and EP/GF-12 higher values of deformation at maximum stress are recorded for samples produced by HL. This trend is probably due to the greater thickness of composite materials made by HL (Figure 13). For samples made by VIP, a slight increase in deformation at maximum stress values is visible at max. stress due to the increasing number of layers of reinforcement. For HL-produced samples, this trend is evident only for AF-reinforced samples. For EP/GF and EP/CF samples, no increase in deformation at maximum stress is visible due to the increasing number of reinforcement layers, probably due to the uneven production conditions in the manual production method.

In Figure 6 shows the dependence of the deformation at failure of the studied composites reinforced with GF, CF, and AF produced by HL and VIP on the number of reinforcement layers. From a comparison of Figures 5 and 6, it is clear that the values of deformation at maximum stress and deformation at failure of composites are very similar. For EP/GF samples, the values of deformation at failure are 2 to 15 % higher than the deformation at maximum stress, indicating that the failure of the samples did not occur at maximum bending stress, but after reaching the maximum the stress decreased until failure. For CF-reinforced composites, the values of deformation at maximum stress and deformation at failure are identical. From this it can be concluded that a brittle fracture of the material occurred. In the EP/AF (VIP) samples as well as in the EP/GF samples, a slightly increased deformation at failure was recorded in comparison with the deformation at maximum stress (2 to 10 %).
Figure 5. Deformation at maximum stress of EP/GF, EP/CF and EP/AF composites produced by HL and VIP on the number of reinforcement layers.

Figure 6. Deformation at failure of EP/GF, EP/CF and EP/AF composites produced by HL and VIP on the number of reinforcement layers.

3.2. Thermal stability of fiber-reinforced epoxy composites

Samples of EP/GF-10 (HL), EP/GF-10 (VIP), EP/CF-10 (HL), EP/CF-10 (VIP), EP/AF-10 (HL) and EP/AF-10 (VIP) were selected for the study of thermal properties. The TG curves of the studied samples are in Figure 7. First derivations of TG curves were also processed for better identification of thermal steps (Figure 8). For samples made by HL, the first step of material decomposition in the range of 300 to 480 °C is visible. This step corresponds to the decomposition of the EP matrix Biresin® CR82 (A) + Biresin® CH80-2 (B). In Figure 8 shows a band at 353 °C for samples made by HL, which probably corresponds to the cleavage of hydroxide groups from the chain. This band is most clearly visible in the EP/CF-10 (HL) sample. The maximum weight loss upon matrix disintegration was recorded at 373 °C. This peak probably corresponds to the complete decomposition of the epoxide chain by cleavage of the amino groups. For samples made by VIP, the first step corresponding to the decomposition of the EP matrix Biresin® CR83 (A) + Biresin® CH80-2 (B) is in the range of 290 to 450 °C. At 336 °C, a band corresponding to the cleavage of the hydroxyl groups is visible on the DTG curves of the VIP-made samples. The maximum weight loss of this step was recorded at 360 °C. At this temperature, the amino groups were probably cleaved from the chain. It is likely that if the VIP-made samples were tempered for a long time, the thermal decomposition of the matrix would take place at higher temperatures. The
second decomposition step corresponding to the decomposition of the fibrous reinforcement is visible only in the samples reinforced with AF. For samples EP/AF-10 (HL) and EP/AF-10 (VIP), the decomposition of the aramid reinforcement occurred in one step in the temperature range 530 to 605 °C. Maximum weight loss was captured at 592 °C. From the performed analysis it can be concluded that the glass and carbon fibers are able to withstand temperatures of at least 1500 °C, since for samples EP/GF-10 (HL), EP/GF-10 (VIP), EP/CF-10 (HL) and EP/CF-10 (VIP), only one weight loss step corresponding to the EP matrix was recorded. From the comparison of the weight losses of the studied samples, it is possible to approximately determine the weight fraction of the EP matrix in the material and thus also the weight ratio of the matrix - reinforcement. In particular, on the DTG curves (Figure 8), a lower weight loss of material is clearly visible in the samples made by VIP in the first decomposition step corresponding to the decomposition of the matrix.

![TG curves](image)

**Figure 7.** TG curves of EP/GF-10, EP/CF-10 and EP/AF-10 composites produced by HL and VIP.

The weight loss of the matrix in the samples made by HL ranged from 43 to 52 % and in the samples made by VIP in the range from 36 to 39 %. It follows that in the samples produced by HL, the content of fibrous reinforcement was on average about 10 % lower compared to the samples produced by VIP.

![DTG curves](image)

**Figure. 8 DTG curves of EP/GF-10, EP/CF-10 and EP/AF-10 composites produced by HL and VIP.**
This statement also confirms that in the second step, during the disintegration of the aramid reinforcement, a higher weight loss was recorded in the sample EP/AF-10 (VIP) than in the sample EP/AF-10 (HL). It can be noted that in the case of laminates produced by HL, the dispersion of weight losses in the first step is substantially larger, which is mainly due to the uneven production. For samples made by VIP, this variance is probably due to the different densities and thus the weight of the reinforcement used.

3.3. Morphology of fiber-reinforced epoxy composites

The morphology of the fracture surfaces of the laminate samples, the morphology of their cross-sections and the morphology of the upper and lower surfaces of the studied samples were also studied on the prepared composite materials. Samples of EP/GF-10 (HL), EP/GF-10 (VIP), EP/CF-10 (HL), EP/CF-10 (VIP), EP/AF-10 (HL) and EP/AF-10 (VIP).

Figure 9. SEM images of glass fiber a), carbon fiber b) and aramid fiber c).
To better understand the mechanical properties of the studied composite materials and especially the interfacial adhesion of the matrix-reinforcement, the surfaces of the fibers from which the used fabric reinforcements were made, were also observed. In Figure 9 are SEM images of glass fiber (Figure 9 a)), carbon fiber (Figure 9 b)) and aramid fiber (Figure 9 c)). Using the SE detector, it is possible to observe the morphology of the fiber surface, and for scanning with the BSE detector, it is possible to monitor the different chemical composition of the material. In BSE images, lower atomic weight elements are displayed darker and higher atomic weight elements are displayed lighter. By comparing the images taken with the SE detector, it is clear that the surface of GF and AF is relatively smooth with slight surface defects. The surface of the CF is visible, which is probably due to the different technological process in the production of this type of fibers. Due to the minimal fragmentation of the CF surface, there is probably a higher adhesion to the EP matrix compared to GF and AF, which probably contributed to the fact that the CF-reinforced compositions were evaluated as the most brittle of the investigated materials. Thanks to scanning from the BSE detector, it can be seen that CF and AF are single-phase and do not contain any unincorporated groups of elements. On the surface of the GF, they are treated with an area formed by elements with lighter atomic weights than the material which forms the majority of the fibers.

The other images (Figure 10) show the fracture surfaces of the studied composite materials after the tensile test. Delamination of the reinforcing phase (fibers) from the EP matrix can be observed in all these images. The most pronounced delamination was recorded in samples reinforced with AF (Figure 10 a), b)), where practically only AF ripped from the matrix is captured in the images. From this it can be concluded that at the interfacial adhesion EP-AF there was the weakest adhesion compared to other examined types of fibrous reinforcement. By comparing these images with the images of the details of the torn GF (Figure 10 a), b)) and CF (Figure 11), it can be observed that in contrast to GF and CF in AF, brittle fiber refraction cannot be observed. It can be observed that these fibers are frayed or split, which is probably due to the fact that AF are polymeric fibers in contrast to GF and CF. At the same time, it points to their amorphous character and high toughness. Significant delamination after the tensile test is also visible in samples EP / GF-10 (HL) and EP / GF-10 (VIP) (Figure 10). In Figure 10 it is possible to see alternating layers of longitudinal and transverse torn GFs torn from the matrix with layers.
of EP matrix. Internal defects in the material caused by air bubbles clogged during the manual production process are visible in the matrix layers. In Figure 10 it is possible to see alternating layers of longitudinal and transverse layers of fibers forming the warp and the attack of the used fabric. Since the SEM image of the fracture surface of the EP/GF-10 (VIP) sample does not recognize larger areas of the matrix than the single phase, it can be stated that a better dispersion of the reinforcing phase was achieved by vacuum supersaturation. As a result, the final thickness of the laminates produced by VIP was also considerably smaller. In Figure 10 it is possible to see GF ripped from the matrix covered with EP matrix residues.

![Figure 11. SEM images of fracture of composite EP/CF-10 (HL) and EP/CF-10 (VIP).](image)

This indicates better interfacial adhesion of EP-GF than EP-AF. In Figure 10 it is possible to see the fracture surfaces of the torn GFs. The figure shows that the fibers cracked, and the crack suddenly widened. A defect is visible on the cross section of one of the fibers. By observing the ridges and rivers leading from this defect, it can be stated that the crack propagation took place from this point. It follows that this site can be referred to as the crack initiation site. In Figure 10 are also visible fracture surfaces broken by GF by a fracture character very similar to those in Figure 10. Using a BSE detector, it is possible to see on the cross-section of one fiber the areas of unincorporated groups formed by elements with higher atomic weights than glass. In Figure 11 are images of the fracture surfaces of CF-reinforced laminate samples. It can be observed that the delamination of these samples was the least pronounced. From this it can be concluded that the bonding of the reinforcing phase and the matrix was the strongest in this type of composites. In Figure 11a) as with the sample EP/GF-10 (HL) (Figure 10a)), the areas of the transverse and longitudinal fibers alternating with the layers of the matrix in which the defects are again visible are visible. On the fracture surface of the sample produced by VIP (Figure 11 b)) the areas of the pure matrix are not recognizable, which again resulted in a lower thickness of the laminate than the equivalent of the produced HL. In Figure 11 are images capturing clear delamination at the reinforcement-matrix interface and clearly visible broken CF due to tensile stress. In Figure 11striae located on the quarry area are also visible. Figure 11 capture torn CFs in the direction of the stress axis of the sample. It can be seen that in the sample EP/CF-10 (HL) (Figure 11 a)) the spaces between the individual fibers filled with EP matrix are significantly larger than in the sample made by VIP. Furthermore, it can be observed that, unlike GF and AF, CFs have a rather irregular cross-section, which
is due to the different way of producing this type of fiber. Using the images from the BSE detector, it can be stated that the CFs are single-phase and do not contain any unincorporated groups of elements.

![SEM images of fracture of composite EP/AF-10 (HL) and EP/AF-10 (VIP).](image)

**Figure 12.** SEM images of fracture of composite EP/AF-10 (HL) and EP/AF-10 (VIP).

The thickness of the produced composite materials was also studied. For all comparable sample types, lower thickness values were recorded for samples made by VIPs because vacuum supersaturation resulted in a lower EP matrix content in the material, Figure 13.

![Graph showing dependence of thickness on number of reinforcement layers.](image)

**Figure 13.** Dependence of the thickness of EP / GF, EP / CF and EP / AF composites produced by HL and VIP on the number of reinforcement layers.

In HL, the excess matrix is extruded from the supersaturated layers of the fabric with a knurled roller, while in VIP it is sucked into the trapping fabric by means of a vacuum. It follows that VIP production is a more effective way to increase the reinforcement-matrix ratio in the laminate. Furthermore, it can
be noted that in contrast to samples made by VIP, where the thickness of the material increases relatively regularly depending on the number of layers of fabric reinforcement (18 to 24 % by adding 2 layers of fabric), samples made by HL increase the thickness by adding 2 layers of fabric ranged from 5 to 31 %. This proves that it is possible to achieve a more uniform thickness and thus more uniform mechanical properties of the produced laminate by the vacuum production method. The lowest thickness values were measured for GF-reinforced samples followed by CF-reinforced samples and the highest values were measured for EP/AF samples.

4. Conclusion
The study of tensile properties shows that in materials made by vacuum supersaturation (VIP) higher values of tensile strength were achieved while maintaining approximately the same values of relative elongation at break. At the same time, significant fluctuations in the values of tensile strength were recorded for samples made by hand supersaturation (HL) with respect to the number of fabric layers, which indicates the unevenness of the production process in this type of production. The highest values of tensile strength and at the same time relative elongation at break were achieved in samples reinforced with aramid fibers (AF). The lowest tensile strength was measured for the glass fiber reinforced (GF) samples and the lowest elongation at break for the carbon fiber (CF) reinforced samples. For most samples, an increase in tensile strength and elongation at break was observed with increasing number of layers of fabric reinforcement. By studying the flexural properties, as in the case of tensile strength, higher values of flexural strength and flexural stress at failure were recorded for samples produced by vacuum supersaturation (VIP). This dependence was most pronounced in the carbon fiber reinforced samples. For most samples, higher values of flexural deformation at maximum stress and flexural deformation at failure were recorded for samples made by hand supersaturation (HL). This dependence was again most pronounced in the carbon fiber (CF) reinforced samples. The highest values of flexural strength and minimum flexural failure of the glass (GF) and aramid fiber (AF) samples were approximately the same.

Using thermogravimetric analysis, information was obtained on the thermal stability of the studied laminates and the degradation temperatures of their components. The epoxy matrix was found to be the first to degrade at approximately 290 °C. Weight loss of aramid fibers (AF) in the range of 530 to 605 °C was also captured. The weight loss of glass (GF) and carbon fibers (CF) was not recorded, so the analysis shows that their degradation temperature is higher than 1500 °C.

By observing SEM images of fracture surfaces of the studied composite materials after the tensile test, it was found that the most significant delamination between the matrix and the reinforcing phase occurred in samples reinforced with AF aramid fibers. From these images, it can be concluded that the highest interfacial adhesion was achieved using carbon fibers (CF) as the reinforcing phase. By studying SEM cross-sectional images, it was found that in the samples produced by the manual production method (HL), there were significantly more defects in the form of air bubbles introduced into the material during production. This could affect the mechanical properties and thickness of these materials. The thickness of the produced laminate samples ranged from 1.381 to 3.921 mm. Lower thickness values were measured on samples made by vacuum supersaturation (VIP). The highest thicknesses were measured in samples reinforced with aramid fibers (AF) and the lowest values of thicknesses were measured in samples reinforced with glass fibers (GF).

These findings can be used in practice to optimize the production of glass, carbon and aramid fiber reinforced laminate products. The subject of further research may be the combination of the types of fiber reinforcement used, or their combination with other types of synthetic or natural types of fiber reinforcement.
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References
[1] SOLOMONS, T. W. G., FRYHLE, C. B. a SNYDER, S. A.: Organic Chemistry. Tampa: Wiley Global Education, 2013. 1272 p. ISBN 1118473671.
[2] THOMAS, R., YUMEI, D., YUELONG, H.: Polymer, 10. January 2008, vol. 49, no. 1, p. 278–294.
[3] JOHNSEN, B. B., KINLOCH, A. J., MOHAMMED, R. D.: Polymer, 12. January 2007, vol. 48, no. 2, p. 530–541.
[4] MANJUNATHA, C. M., TAYLOR, A. C., KINLOCH, A. J.: Composites Science and Technology, January 2010, vol. 70, no. 1, p. 193–199.
[5] WETZEL, B., ROSSO, P., HAUPERT, F.: Engineering Fracture Mechanics, November 2006, vol. 73, no. 16, p. 2375–2398.
[6] GOJNY, F. H., WICHMANN, M. H. G., KÖPKE, U.: Composites Science and Technology, November 2004, vol. 64, no. 15, p. 2363–2371.
[7] GOJNY, F. H., WICHMANN, M. H. G., FIEDLER, B.: Composites Science and Technology, December 2005, vol. 65, no. 15–16, p. 2300–2313.
[8] HSIEH, T. H., KINLOCH, A. J., MASANIA, K.: Polymer, 10. December 2010, vol. 51, no. 26, p. 6284–6294.
[9] MANJUNATHA, C. M., TAYLOR, A. C., KINLOCH, A. J.: Composites Science and Technology, January 2010, vol. 70, no. 1, p. 193–199.
[10] SONG, J. H.: Composites Part B: Engineering, 15. September 2015, vol. 79, p. 61–66.
[11] HOLMES, M.: Reinforced Plastics, November–December 2013, vol. 57, no. 6, p. 24–29.
[12] TRAN, T. K., KIM, D. J., CHOI, E.: Cement and Concrete Research, September 2013, vol. 63, p. 54–66.
[13] GUSTIN, J., JONESON, A., MAHINFALAH, M.: Composite Structures, August 2005, vol. 69, no. 4, p. 396–406.
[14] ABOUNAIM, M., DIESTEL, O., OFFMANN, G.: Composites Science and Technology, 28. February 2011, vol. 71, no. 4, p. 511–519.
[15] TEMENOFF, J. S., MIKOS, A. G.: Biomaterials: The Intersection of Biology and Materials Science. Lebanon: Prentice Hall, 2008. 478 p. ISBN 9780132350440.
[16] Technický list fy. TRANSTECH TOOLING, s. r. o.: Biresin® CR82 : pryskyřice na tvorbu kompozitů. Popůvky, 2009.
[17] Technický list fy. TRANSTECH TOOLING, s. r. o.: Biresin® CR83 : pryskyřice na tvorbu kompozitů. Popůvky, 2009.