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ASSESSMENT OF THE APPLICABILITY OF BASALT FIBER-REINFORCED EPOXY COMPOSITES IN VEHICLE CONSTRUCTION

Summary. This article presents a description of the properties of basalt fibers and polymer composites containing basalt fibers. Basalt fibers are seen as a potentially beneficial component in composite development, especially for vehicles in transport applications. The article also presents the results of the mechanical properties investigation of the glass-epoxy and basalt-epoxy composites. The composites for testing were prepared using the popular hand lay-up method. The samples were cut from prepared plates using abrasive water jet methods. The obtained samples were tested to evaluate their flexural strength and interlaminar sharing strength. The achieved mechanical properties were compared.

1. INTRODUCTION

Increasing performance, lowering wear and tear, and enhancing safety requirements for vehicles, as well as increasingly strict legislation in a climate-environment area, have required the exploration of new fiber-reinforced polymer composites for vehicle structure [1].

A composite material is a material made from various (two or more) constituent materials, which is macroscopically monolithic, but on a microscopic scale, its components remain separate and distinct from each other [2, 3]. Each component material has unique properties. A well-designed composite material should have better properties than each of the component materials taken separately. Composites, with their high specific modulus and strength, are ever-increasing in use in day-to-day applications; new materials have been introduced at a fast pace, mainly in the aerospace, aeronautic, naval, and automotive industries [4].

Polymer matrix composites (PMCs) for engineering and construction applications are made from high-strength fibers, which are included in a polymer resin. Of course, the properties of these composites depend on the materials used.

In some ways, the PMC materials used in vehicle manufacturing are better than steel. An area of increasing recognition is the use of aluminum in vehicles, which is used for load-bearing components and powertrain components [5-8]. However, problems with manufacturing parts in aluminum and some of the properties of this material limit its use. These problems and disadvantages include low electrical resistance, welding difficulties, low ductility, and low formability in plastic work [9].

An advantage of PMCs is that their structure can be designed to be lightweight yet mechanically strong. Such a structure can provide high levels of safety with low energy consumption. PMCs weigh about 20-35% less than steel; however, their strength and Young's modulus values could be comparable to or even greater than those of steel. In addition, the strength-to-density ratio of this composite material is very favorable for composites. The aging process of polymer composites is different from that of steel and is incredibly slow, which is another advantage of PMCs.

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Owing to their mechanical properties, especially their high strength and stiffness and low weight, polymer composites are often used in the aviation and aerospace industry. Compared to embossed sheets of steel in automobile applications, polymer composites, especially those with a multilayer structure, can be made to absorb more energy in accidents for any type of vehicle. Unlike other materials, changing the matrix or filler material of a composite or changing the structure of the reinforcement, its amount, form, etc., makes it possible to change the polymer's properties. The considerable flexibility of composite design and manufacture allows larger parts to be produced, parts that previously often had to be assembled from several smaller parts.

For these reasons, composites are considered for the development of light, safe, and low-energy consumption vehicles.

Price is the most important aspect to consider when making vehicles. This includes taking into account the costs associated with the full lifecycle of a vehicle. The problem with polymer-fiber composites is that they have been created mainly for the aviation industry, where the high cost is not the most important aspect of production. The costs of the most well-known hi-tech composites, such as carbon fiber epoxy composites, are at least 20 times higher than those of steel. These composites are popular for Formula 1 vehicle manufacturing or for high-end/luxury vehicles, but the common automotive industry is unlikely to use them until the price of carbon fiber drops significantly. Despite this, the demand for carbon composites continued to increase in 2021 and 2022 [10].

The share of composites for medium and high-volume production is increasing, although batch production is more sensitive to the cost of high-volume production equipment. The reason for this growth is the strong interest in products made from continuous glass fiber-reinforced polymers (e.g., leaf springs), as well as composites made from chopped fibers. Composite vehicle parts are created using various technologies, including sheet molded composites, bulk-molded composites, and injection-molded composites [10].

A common example of the use of composites in the transportation industry is the fiberglass panels used as part of the bodywork in cars and trucks and, recently, even in trains. The German ICE4 (Siemens ICx) and the Polish Pendolino ED250 (ALSTOM EMU250) are examples of high-speed trains that have a nose cone made of composites. The use of composite materials instead of steel in the nose cone reduces energy consumption because it minimizes the weight of the car and axle loads, improves the aerodynamics of the train, and increases the car's capacity. When composites are used, the outer shell of the driver's cab can be manufactured as a single component of the locomotive. This solution simplifies assembly and reduces vehicle production time. In addition, Siemens recognizes the potential of composites by planning their use in railcar couplings, drive components, and energy absorbers. Such absorbers will be lighter and have better energy-absorbing characteristics than the steel absorbers currently used [11].

Hanvit 200, a South Korean experimental high-speed tilting train, has a car body made of a composite sandwich structure. Additionally, composite sheets have a steel frame bonded into them. This multicomponent structure is combined in one of the world's largest autoclaves. The use of sandwich composites could reduce the weight of a railcar by about 28% compared to conventional steel frame construction [2, 12-14].

In summarizing the state of knowledge on composites in the transport industry, it can be stated that:

- The costs of producing fibers are relatively high.
- Composites are widely used in cars, trucks, aircraft, and even trains. Composites have less weight and more strength than steel, resulting in greater energy efficiency and a longer service life. The energy savings resulting from the lightweight construction of vehicles will make a significant contribution to the environment and, in particular, the conservation of nonrenewable fossil fuels.
- The growth of low-cost, sustainable fibers is an exciting research area with excellent prospects for the transportation industry.

In the last two decades, information about a new type of polymer-basalt composites has emerged in which basalt reinforcement is used in place of glass fibers [15-17]. Future research on technical fibers can focus on the purpose of possibility and practicality in the exploitation of basalt fibers in polymer composites as an advantageous alternative for applications in which only glass, carbon, and aramid fibers currently have a true market.

2. BASALT AS A NEW-OLD ALTERNATIVE REINFORCEMENT FOR COMPOSITES

Basalt is a volcanic rock that is found in most countries around the world. Since ancient times, it has been used for various architectural ornaments. Today, the possibility of using basalt fibers as a substitute for asbestos is being explored.

The first scientist to work on obtaining fibers from basalt rock was Frenchman Paul Dhé. The technology was patented in the United States in 1923. Basalt fibers were initially developed by the Moscow Research Institute of Glass and Plastics between 1953 and 1954 [18]. In the early 1960s, the United States and the Soviet Union (USSR) began researching applications of basalt fiber in military equipment.

Basalt fiber research has been taken up by glass companies in the northwestern United States. This research has resulted in a number of patents filed by Owens Corning Corporation and several other companies. Unfortunately, large private businesses focused on glass production and, around 1970, lost interest in basalt as an alternative material.

At this time, research in Eastern Europe was confined by the USSR and placed in Kiev, Ukraine, where the technology for producing fibers from basalt was developed in complete secrecy. The first industrial fiber melting furnace was built at the Ukrainian Fiber Laboratory in 1985 [5].

After the collapse of the USSR in 1991, the results and technologies on basalt fibers were declassified.

Today, production and wholesaling occur in former socialist countries. Currently, only about eight companies in the world are involved in the production and distribution of basalt fibers.

Basalt fibers, which are characterized by high mechanical and high-temperature strengths, may be an alternative to current engineered fibers despite their recent arrival on the technology market.

Basalt proponents claim that their products give a fiberglass-like performance and, in selected uses, offer makers a less costly replacement for carbon fiber in applications, particularly for a high-tech product design. Basalt fiber has a dark golden-brown color, which in the resin matrix is black and looks almost the same as carbon fiber in epoxy resin composites.

As can be seen, basalt fiber-reinforced composites are not a new material, but their usage is innovative in various areas like civil engineering, energy efficiency, motorization, aviation and aerospace due to their desirable mechanical, chemical, and thermal properties.

Typically, glass or carbon (graphite) fibers are used for the reinforcement of standard PMCs. Carbon (graphite) fibers are commonly used in components for which higher strength and stiffness (Young's modulus) are required. The difference between carbon and graphite fibers is the higher strength of carbon fibers, while graphite fibers have a higher stiffness. Carbon (graphite) fibers have some disadvantages, such as a lower elongation at break and impact strength compared to glass fibers.

Basalt fibers could become competitive with glass fibers and be a potential reinforcing material for PMCs [19].

2.1. Production of basalt fibers

Basalt fibers are manufactured using a continuing operation, which is similar in many ways to the glass fiber production process. Mined basalt rock is first crushed, then rinsed and fused in gas-heated furnaces. Minerals such as basalt are found in volcanic magma that has been cooled. A magma's melting temperature varies between 1500 and 1700 °C [18, 20, 21]. In addition to plagioclase and pyroxene, basalt also contains olivine and fluorspar. The temperature at which the quenching process is conducted plays a substantial role in the quality of the basalt state and in achieving a more or less complete crystallization of the basalt state.

Both basalt and glass are silicates, which transform from liquids into amorphous solids upon cooling. However, basalt has a unique crystalline structure depending on the local lava flow circumstances at each place. Depending on the location of mineral deposits, basalt rock varies in terms of its chemical composition and phase proportion. The cooling rate also influences the crystalline structure of basalt fibers.

Despite basalt's widespread availability, only a small number of places have basalt that has been certified as acceptable for the production of continuous fibers.

The base costs of basalt fiber vary depending on the type and quality, the manufacturing process, and the qualities of the finished product. The chemical and mechanical qualities of raw materials affect their cost, as their cost is based on their composition. The variation in composition and element concentration is attributed to differences in thermal and chemical stability, as well as mechanical and physical qualities [22].

The production method of basalt fibers is similar to glass fiber technology but with lower energy consumption and no additives. Thus, it is less costly and more environmentally friendly than glass fiber production.

Basalt fibers can be formed in one of three ways:

- Volcanic rock as a raw material is melted in a furnace. Then, the molten material is driven through platinum and rhodium alloy dies with microscopic apertures to produce a large number of fibers at the same time. This continuous spinning process can provide fibers in chopped or continuous form.
- Blowing melt technology is used for the production of short-length basalt fibers with lower mechanical properties and low cost [23].
- The dielectric heating-based melt-spinning method is used to produce fibers on a laboratory scale [24].

2.2. Basalt fiber properties

Interestingly, basalt fibers combine ecological safety, natural longevity, good mechanical properties, and high-level thermal characteristics (Table 1). Basalt fiber is a non-polluting, environmentally friendly substance. The "manufacturing-related" greenhouse gases were released millions of years ago during the magma eruption, and today, basalt can be considered an inert material that does not react toxically with air and water. Basalt is also non-flammable and resistant to explosion [25].

Table 1

Physical properties of various fibers [28, 29]

<table>
<tr><th>Physical property</th><th>Basalt</th><th>E-Glass</th><th>S-Glass</th><th>Silica</th></tr>
<tr><td>Density [Mg/m^3]</td><td>2.7</td><td>2.57</td><td>2.48</td><td>2.15</td></tr>
<tr><td>Linear thermal expansion coefficient [ppm/°C]</td><td>8.0</td><td>5.4</td><td>2.9</td><td>0.05</td></tr>
<tr><td>Tensile strength [MPa]</td><td>4840</td><td>3450</td><td>4710</td><td>4750</td></tr>
<tr><td>Young's modulus [GPa]</td><td>89</td><td>77</td><td>89</td><td>66</td></tr>
<tr><td>Elongation at break [%]</td><td>3.15</td><td>4.7</td><td>5.6</td><td>1.2</td></tr>
<tr><td>Compression strength [MPa]</td><td>3792</td><td colspan="2">3033</td><td>3516</td></tr>
<tr><td>Max. operating temperature [°C]</td><td>982</td><td colspan="2">650</td><td>1100</td></tr>
<tr><td>Min. operating temperature [°C]</td><td>-260</td><td colspan="2">-60</td><td>-170</td></tr>
<tr><td>Heat conductivity [W/m K]</td><td>0.031-0.038</td><td colspan="2">0.034-0.04</td><td>0.035-0.04</td></tr>
<tr><td>Melting temperature [°C]</td><td>1450</td><td colspan="2">1120</td><td>1550</td></tr>
<tr><td>Fiber diameter [µm]</td><td>9-23</td><td colspan="2">9-13</td><td>9-15</td></tr>
<tr><td>Humidity absorption [%]</td><td><0.1</td><td colspan="2"><0.1</td><td><0.1</td></tr>
</table>

Moreover, basalt fibers are resistant to ultraviolet light, high-energy ionizing radiation, and acids, and they retain their characteristics at sub-zero temperatures.

Basalt fibers have greater adhesion with the matrix of organic resins and inorganic compounds compared to other types of fibers. This affects the ability of basalt-reinforced composites to achieve higher mechanical properties [26]. The bond strength of basalt fibers to epoxy resin is higher than for E-glass and carbon fibers, both for fibers without surface treatment and for silane-coated fibers [27].

The data presented in Table 1 [28,29] shows that the tensile strength and Young's modulus of basalt fibers are higher or equal to those of E-glass, S-glass, and silica and that basalt fibers have the widest operating temperature range. This set of properties makes basalt fiber-reinforced polymer composites suitable for use in civil engineering and means of transport.

3. EXPERIMENT DETAILS

The plan for the experiment was to compare four composites with the same epoxy matrix but with four different reinforcements. The first two composites were laminates with basalt fabric reinforcements. The third and fourth composites were made with glass reinforcements. Mechanical properties determined in bending and interlaminar shear resistance tests were chosen as a comparison criterion. Properties such as bending (flexural) strength and Young's modulus are commonly used to assess the performance characteristics of composites.

The interlaminar shear strength test determines a composite's resistance to delamination under shear pressures parallel to the laminate layers and, hence, to the adhesive/adherent interface. For this reason, it is used to assess the fabrication quality of composites.

Determining the mechanical properties makes it possible to test whether basalt composites are as good as glass composites when used as a cover or as load-bearing parts of a structure.

The material property score is the average of five test samples for a given tested property. This number is derived from the technical standards of testing for polymer composite materials.

3.1. Materials

In the tests, a basalt fabric was used that is theorized to have good strength and fire and corrosion resistance. E-glass fabric, which is widely used in the manufacture of composite materials and has a high degree of processing technology development, was chosen as the comparative material. A comparison of the fabrics is included in Table 2.

Table 2

Properties of fabrics

Fabric	Basalt		Glass	
Composite →	I	II	III	IV
Fabric density [g/m^2]	210±10	410±10	200±12	450±27
Fabric weave	plain	plain	plain	plain
Type of fiber finish	-	-	silan	silan
Composite plate thickness [mm]	5.0	1.6	5.0	1.6

A microscopic and chemical analysis of the basalt fabric/fibers used in the tests is shown in Fig. 1. The analysis was performed with the use of a Phenom Desktop scanning electron microscope (SEM) with an energy-dispersive X-ray spectrometer (EDS).

a) b)

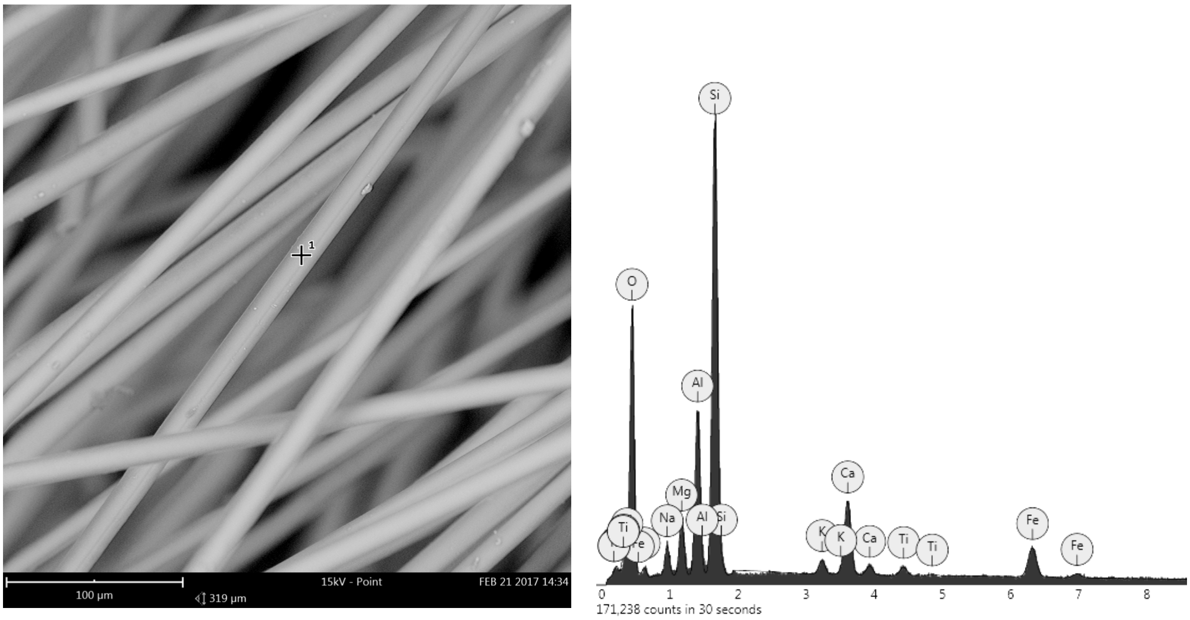

Fig. 1. Microscopic analysis of basalt fabric: a) SEM view of individual basalt fibers and b) EDS spectrum of the chemical composition analysis of fibers

The chemical analysis is consistent with data reported in the literature [30]. The analysis using SEM microscopy software has revealed that the diameter of the basalt fibers ranges from 5.60 to 16.60 µm, with an average value of 12.2 µm.

The composites mentioned in Table 2 were developed using Epidian 6 epoxy resin and a Z1 hardener mixed with a weight proportion of 100:13 (both obtained from Organika Sarzyna, Poland).
Epidian 6 is a 700 molecular weight epoxy resin derived from bisphenol A and epichlorohydrin. The hardener, Z1, is the trade name of the chemical compound known as triethylenetetramine.

Previous research [31] describes the key features of this epoxy resin system. This epoxy resin is a typical polymeric material used as a composite matrix in transportation and construction applications.

3.2. Forming composite samples

The composite panels were made using a hand lay-up approach. Because it involves the least amount of equipment, the hand lay-up method is the most popular and least expensive open-molding method. Hand-laid fiber reinforcements were placed in a mold, and then the resin was added using a brush or roller. Pouring, brushing, or rolling on the laminating resin system are all methods of application. Aluminum or polytetrafluoroethylene rollers are utilized to consolidate the laminate, properly moisten the reinforcement, and remove entrapped air. The thickness of the laminate is increased by adding additional layers of fiber reinforcement. The plates of composites II and IV were made to a thickness of 1.6 mm, while the plates of composites I and III were made to a thickness of 5 mm.

Before the fabrication process, a beeswax-based release liner was applied to facilitate the removal of the finished panels from the mold. The process was repeated three times at 15-minute intervals, ending with the polishing of the cavity to evenly distribute the agent. After this time, another 30 minutes were allowed to pass for the resulting layer to dry. Composite panels were then annealed at 70 °C for one week to achieve a high level of resin cure, allowing the mechanical properties of the matrix to be close to the theoretical maximum.

Specimens for mechanical tests were cut from the composite plates. The samples were cut to size according to the recommendations of EN ISO 14130 and EN ISO 14125 standards. The plates were cut using the water abrasive jet method. This method was chosen because, of all known methods, it causes the least damage to the edges of the specimen and does not generate adverse thermal phenomena. Five samples were taken from each composite for testing, as recommended by the following standards: EN ISO 14130, EN ISO 14125, and EN ISO 178. Of the samples, those with the most similar dimensions were selected. Differences in specimen thickness resulting from manufacturing technology were taken into account in the strength calculations.

3.3. Tests

The tests involved two strength tests: a flexural strength test and an interlaminar wall strength test. Both tests are basic tests used to determine the suitability of a composite for vehicle applications. The tests were conducted using a Zwick/Roell Z020 machine in a three-point bending system.

The flexural strength test was performed in accordance with the EN ISO 14125 standard recommendations. For composite specimens I and III, the distance of the lower supports was 80 mm. For composites II and IV, the distance was 25 mm. These differences are due to the adjustment of the distance of supports to the thickness of the specimens. The speed of crosshead movement was 5 mm per minute. Table 3 presents the results of the flexural strength test; the standard deviations of the results are indicated as S(x).

Table 3

Results of the tensile test

Composite	Sample No	Young modulus E [MPa]			Flexural strength σ [MPa]			Deformation at break ε_{fM} [%]		
		Value	Average	S(x)	Value	Average	S(x)	Value	Average	S(x)
I (epoxy-basalt composite)	IA	19,300	18,800	687	405	401	9.26	2.5	2.6	0.04
	IB	18,400			400			2.6		
	IC	18,100			395			2.6		
	ID	19,900			417			2.6		
	IE	18,300			390			2.6		
II (epoxy-basalt composite)	IIA	17,480	16,240	785	425	422	19.94	5.3	5.2	0.24
	IIB	16,190			455			5.5		
	IIC	16,330			415			5.1		
	IID	16,220			423			5.0		
	IIE	15,000			393			4.8		
III (epoxy-glass composite)	IIIA	16,200	17,400	1127	418	447	14.91	3.0	3.0	0.15
	IIIB	15,900			457			3.3		
	IIIC	18,100			447			2.9		
	IIID	18,700			454			2.9		
	IIIE	18,100			458			3.0		
IV (epoxy-glass composite)	IVA	15,970	16,470	597	406	402	7.50	5.0	4.7	0.15
	IVB	15,240			411			4.8		
	IVC	16,425			395			4.6		
	IVD	15,730			392			4.6		
	IVE	16,990			408			4.7		

Another comparative test employed was the interlaminar shear test (Table 4). The load method for this test is identical to the bending test. The only significant difference between the two tests is the much smaller spacing between supports and the test crosshead speed of only 1 mm per minute. However, due to the low stiffness of the composite II and IV samples caused by their small thickness (see Table 2), it was not possible to determine their shear force.

Table 4

Results of the interlaminar shear test

Composite	Sample number	Shear stress τ [MPa]	Average τ [MPa]	S(x)
I (epoxy-basalt composite)	IA	35.80	35.50	0.58
	IB	35.30		
	IC	34.50		
	ID	36.20		
	IE	35.80		
III (epoxy-glass composite)	IIIA	29.00	30.10	1.49
	IIIB	32.80		
	IIIC	29.10		
	IIID	30.70		
	IIIE	29.00		

4. ANALYSIS OF TEST RESULTS

The stress-strain curves determined in the bending curve test have a similar shape for both glass fiber laminates and basalt fiber laminates (Fig. 2).

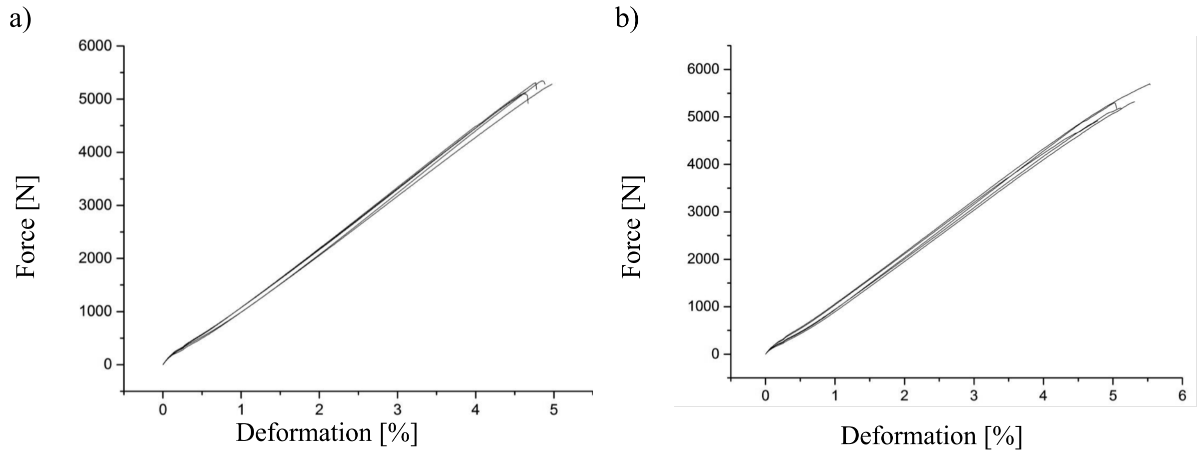

Fig. 2. Comparison of the bending curves of glass and basalt composites

In this test, the bending strength value is of particular importance. In this regard, none of the composites stands out significantly. However, it is necessary to compare composite I with composite III and composite II with composite IV since these pairs have similar weights. Slight differences between composites I and III may result from the density difference of 40 g/m^2, which may influence the mechanical properties of these composites.

The situation is similar for Young's modulus (Fig. 3a). The extension at the break is variable (Fig. 3b). Meanwhile, for composites I and III, higher elongation at break is achieved for glass composites. In composites II and IV, higher values were obtained for basalt composites.

The results obtained from the bending test indicate that the strength properties of both composites determined in this test are similar; however, the higher strength of composites reinforced with basalt fibers indicated in some of the literature or in producers' catalogs was not observed.

In calculations performed on the basis of the interlaminar shear strength test, a slight difference of 5.4 MPa (about 8%) in favor of basalt composites can be observed in this respect.

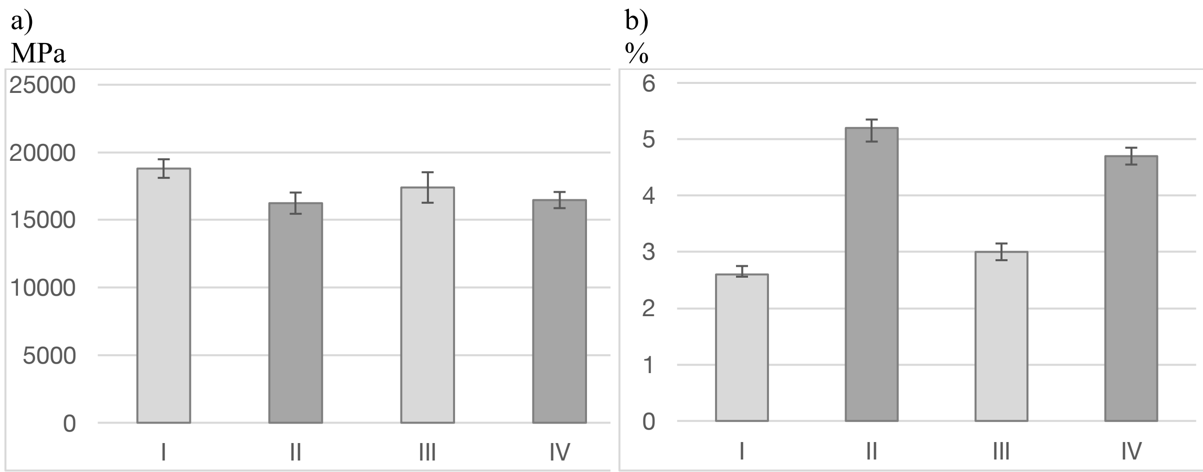

Fig. 3. Comparison of Young's modulus (a) and elongation at break (b) of composite samples

5. CONCLUSIONS

Based on the results of the tests conducted on epoxy-basalt and epoxy-glass composite laminates, the following conclusions were formulated:

- Despite the theoretically better strength properties of basalt fibers relative to glass fibers, the obtained bending strength of basalt fiber-based composites was similar to or even lower than that of glass fiber-based composites.
- The results of the interlaminar shear strength tests indicate that the basalt composites have a higher shear strength by about 8%.
- Considering the wide variety of properties in the composite products made by a hand lay-up method, both composites have similar strength properties.
- Continuing the study with a more accurate match of the utilized fabrics will eliminate doubts about the effect of fabric differences on the resulting properties of composite materials.
- Basalt fiber-based composites could replace glass fiber-based composites in transport applications, especially as materials for vehicle body shells and structural parts.

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