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# Improving the reliability of equipment of the oil and gas transportation complex through the use of reinforced epoxy composites

***A.V. Buketov[1], O.O. Sapronov[1], V.A. Kyrylovych[2], O.V. Sharko[1], K.M. Klevtsov[1], A.V. Sapronova[1], N.M. Buketova[1], E.S. Appazov[1], R.T. Bishchak[3], O.V. Akimov[1], V.V. Sotsenko[1], K.O. Dyadyura[4], O.A. Pastukh[5], O.V. Totosko[5], P.O. Vorobiov[1], Yu.M. Shulga[6], V.Yu. Strelchenko[1], A.G. Kulinich[1], V.I. Palagniy[1], V.L. Aleksenko[1], O.M. Bezbakh[1], D.V. Zhytnyk[1], A.L. Simonenkov[1], A.A. Ivanov[1], I.A. Seliverstov[7], S.R. Seliverstova[1], H.H. Doshchenko[1], B.O. Maslyiak[8], K.Yu. Yurenin[1]***

[1]Kherson State Maritime Academy
Legal address: 20, Nezalezhnosti Ave., Kherson, Ukraine, 73000, Ukraine
Actual address: 99, Kanatna St., Odesa, Ukraine, 65039, Ukraine
[2]Zhytomyr Polytechnic State University
103, Chudnivska St., Zhytomyr, Ukraine, 10005, Ukraine
[3]Ivano-Frankivsk National Technical University of Oil and Gas
15, Karpatska St., Ivano-Frankivsk, Ukraine, 76019, Ukraine
[4]Odesa Polytechnic National University
1, Shevchenko Ave., Odesa, Ukraine, 65044, Ukraine
[5]Ternopil Ivan Puluj National Technical University
56, Ruska St., Ternopil, Ukraine, 46001, Ukraine
[6]Danube Institute of the National University "Odesa Maritime Academy"
15, Myru Ave., Izmail, Odesa Region, Ukraine, 68600, Ukraine
[7]Kherson National Technical University
Legal address: 24, Beryslavske Shosse, Kherson, Ukraine, 73000, Ukraine
Actual address: 11, Instytutska St., Khmelnytskyi, Ukraine, 29016, Ukraine
[8]West Ukrainian National University
11, Lvivska St., Ternopil, Ukraine, 46009, Ukraine
Corresponding author e-mail: buketov@tntu.edu.ua

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The article examines the influence of different types of reinforcing fabrics (basalt, carbon, glass) on the mechanical properties of epoxy composites intended for transportation applications. It has been experimentally confirmed that basalt fabric provides higher flexural strength and impact toughness compared to glass fabric due to improved adhesion to the epoxy matrix. Plasticization of the epoxy resin with aliphatic resin DEG-1 allows increasing the elas-

tic modulus by 16–24%, and the flexural strength – up to 592 MPa, depending on the fabric type. The hybrid "basalt–carbon–basalt" structure proved to be more effective than the "carbon–basalt–carbon" configuration due to optimal stress distribution under bending. The introduction of carbon nanotubes (0.05%) into the plasticized matrix increases the elastic modulus by 35.3% and the impact toughness by 50.8% due to the formation of a three-dimensional reinforcing network. The optimal number of reinforcing layers is 6–8: in this case, maximum values of the elastic modulus (46–48 GPa) and impact toughness (184–188 kJ/m²) are achieved. A further increase in the number of layers (beyond 8) leads to a deterioration of mechanical characteristics due to the accumulation of internal defects and the risk of delamination.

**Keywords:** polymer, plasticizer, epoxy resin, filler, nanodisperse and microdisperse powders, reinforcing fabrics, mechanical properties, composite.

**Підвищення надійності обладнання газо-нафтотранспортного комплексу шляхом застосування армованих епоксидних композитів**. *А.В. Букетов, О.О. Сапронов, В.А. Кирилович, О.В. Шарко, К.М. Клевцов, А.В. Сапронова, Н.М. Букетова, Е.С. Аппазов, Р.Т. Біщак, О.В. Акімов, В.В. Соценко, К.О. Дядюра, О.А. Пастух, О.В. Тотосько, П.О. Воробйов, Ю.М. Шульга, В.Ю. Стрельченко, А.Г. Кулініч, В.І. Палагній, В.Л. Алексенко, О.М. Безбах, Д.В. Житник, А.Л. Симоненков, А.А. Іванов, І.А. Селіверстов, С.Р. Селіверстова, Г.Г. Дощенко, Б.О. Маслияк, К.Ю. Юренін*

У статті розглянуто вплив різних типів армуючих тканин (базальтової, вуглецевої, скляної) на механічні властивості епоксидних композитів, призначених для транспорту. Експериментально підтверджено, що базальтова тканина забезпечує вищу міцність на згин та ударну в'язкість композитів порівняно зі скляною завдяки покращеній адгезії до епоксидної матриці. Пластифікація епоксидної смоли аліфатичною смолою ДЕГ-1 дозволяє збільшити модуль пружності на 16–24%, а міцність при згині – до 592 МПа залежно від типу тканини. Гібридна структура зразків «базальт–вуглець–базальт» виявилася ефективнішою за конфігурацію «вуглець–базальт–вуглець» завдяки оптимальному розподілу напружень при згинанні. Введення вуглецевих нанотрубок (0,05%) у пластифіковану матрицю підвищує модуль пружності на 35,3%, а ударну в'язкість – на 50,8% завдяки формуванню тривимірної армуючої сітки. Оптимальна кількість шарів армування у композиті становить 6–8: при цьому досягаються максимальні значення модуля пружності (46–48 ГПа) та ударної в'язкості (184–188 кДж/м²). Подальше збільшення кількості шарів у композиті (понад 8) призводить до погіршення механічних характеристик через накопичення внутрішніх дефектів та ризик розшарування.

## *1. Introduction*

Today's standards for the use of vehicles, especially those used for transporting gas and oil, require not only easy formation and application of protective layers, but also increased wear resistance and a long service life. Existing anti-corrosion and anti-cavitation coatings often do not satisfy consumers due to their low efficiency during long-term operation in aggressive environments [1-45]. Therefore, there is a need to create advanced composites with high resistance to wear and corrosion, low fatigue creep, and improved mechanical properties.

The most sought-after composites are those based on plasticized epoxy resins containing fine-dispersed fillers [2-14, 28]. Such materials can provide reliable protection against hydro-abrasive wear and corrosion, as well as increased resistance to cavitation and strength when in contact with chemically active substances.

A significant role here is played by the use of composites reinforced with glass, carbon, or basalt fabrics, which demonstrate low creep under long-term loading. Studies [21] have shown that carbon fabrics in epoxy plastics increase specific strength and stiffness, reducing creep both in air and in aggressive conditions. Basalt fabrics create a network in composites that is resistant to chemical influences, contributing to the reduction of residual stresses. Glass fabrics form a reinforcing framework that prevents the initiation and propagation of cracks, thus preventing material fatigue under loads.

It is worth noting that, in addition to reducing creep, the use of these fabrics increases the resistance of materials to hydro-abrasive wear. Furthermore, reinforced composites better withstand pulsating hydrodynamic impacts, which is important for operation under cavitation conditions, since all three types of fibers form a strong bond with the epoxy matrix without defects at the phase interface [38].

Thus, a promising direction is the combined reinforcement of epoxy composites with carbon, glass, and basalt fabrics to achieve a synergistic effect – the simultaneous increase of resistance to creep, corrosion, hydro-abrasive wear, and cavitation.

The optimal reinforcement scheme should be chosen depending on the operating condi-

tions. For example, in a marine environment with hydro-abrasive effects and cavitation, it is advisable to use multilayer composites. Each layer should enhance certain properties of the material, taking into account the nature of the fabric, which will slow down both surface and deep destruction of the product. Consequently, reinforcing fabrics make it possible to create epoxy composites with predictable characteristics for operation in extreme conditions. The aim of this research is to optimize multilayer reinforcement schemes to achieve maximum synergistic effect by comprehensively improving the properties of composites through a combination of different types of fibers.

## 2. Experimental

Epoxy composites were formed based on a plasticized epoxy matrix. It has been experimentally proven that in order to improve the rheological and mechanical properties of composite materials (CM), a plasticizer in the form of aliphatic resin DEG-1 (12%) must be introduced into the epoxy oligomer (100%). The composition should be polymerized with PEPA hardener in an amount of 12%. To improve the mechanical and thermophysical properties of CM, nano- and micro-dispersed powders are introduced into the plasticized epoxy binder, independently of each other. It was found that carbon nanotubes (MWCNT) in an amount of 0.05% are advisable as nanoparticles, and chromium oxide with a content of 15% is advisable as a micropowder.

During the formation of polymer compositions, the epoxy resin DER 331 (ISO 9001) was chosen as the basis, which is the reaction product of epichlorohydrin and bisphenol A. DER 331 is a German analogue of the epoxy resin ED-22, which is produced by the Olin Corporation Company (Germany).

In order to improve the rheological properties of the epoxy binder, the aliphatic resin DEG-1 (TU 2225-390-04872688-98) was introduced into the DER 331 resin as a plasticizer. DEG-1 is introduced into the composition of epoxy resins as a plasticizer and modifier, which has the properties of an active diluent, gives the resin elasticity, impact strength and resistance to temperature changes. DEG-1 resin is well combined with epoxy resin.

Polyethylenepolyamine (PEPA) (TU 2413-357-00203447-99) was used to cure epoxy compositions. The chemical formula of PEPA is as follows: $H_2N(CH_2CH_2NH)nH$. It should be noted that PEPA is a widespread and economical hardener for epoxy resins. It has a pronounced color from light yellow to dark brown. It is characterized by low polymerization exothermicity.

We also used nanotubes in the form of MWCNT powder, developed by Guangzhou Hongwu Material Technology Co., Ltd. (China). MWCNT nano-powder is nano-class graphite crystals, mono- or multilayer flaky graphites in the form of MWCNT. Multilayer nanotubes were used in the work. MWCNT has special properties and can be used in electronics, mechanical engineering, medicine, energy, chemical industry, optics and other industries when using polymer CM. MWCNT have extraordinary strength and unique mechanical and electrical properties, which makes them effective additives in the production of polymer composites.

As a microdispersed additive, chromium oxide powder ($Cr_2O_3$) with a particle size of 10-20 μm was used in the work. Green chromium oxide, also known as chromium (III) oxide and chromium oxide (ISO 4621:1986), is a green crystal of the hexagonal crystal family or an amorphous powder with a metallic luster. It is insoluble in water, alcohols, acids and alkalis, soluble in a hot solution of alkali metal bromate. It is resistant to light, atmosphere, high temperature and aggressive gases, and also has magnetic properties.

The breaking strength, flexural modulus of elasticity, and impact toughness of the materials were investigated. The indicators of tensile and flexural breaking strength, as well as the modulus of elasticity, were determined according to ASTM D 790–03. The impact toughness of the CM was studied under impact using the Charpy method without a notch (ISO 179-1) on an MK-30 pendulum impact testing machine. Additionally, the density was determined by the immersion method according to ISO 1183. Hardness was measured using the Shore Durometer method according to ASTM D2240.

## 3. Results and Discussion

Within the framework of the study, the mechanical characteristics of composite materials (CM) reinforced with various fabrics were analyzed. A multi-stage systematic approach was applied: first, samples of CM reinforced with the same type of fabric and bonded with a plasticized matrix were studied. At subsequent stages, composites with different fiber combinations were analyzed, with mixtures contain-

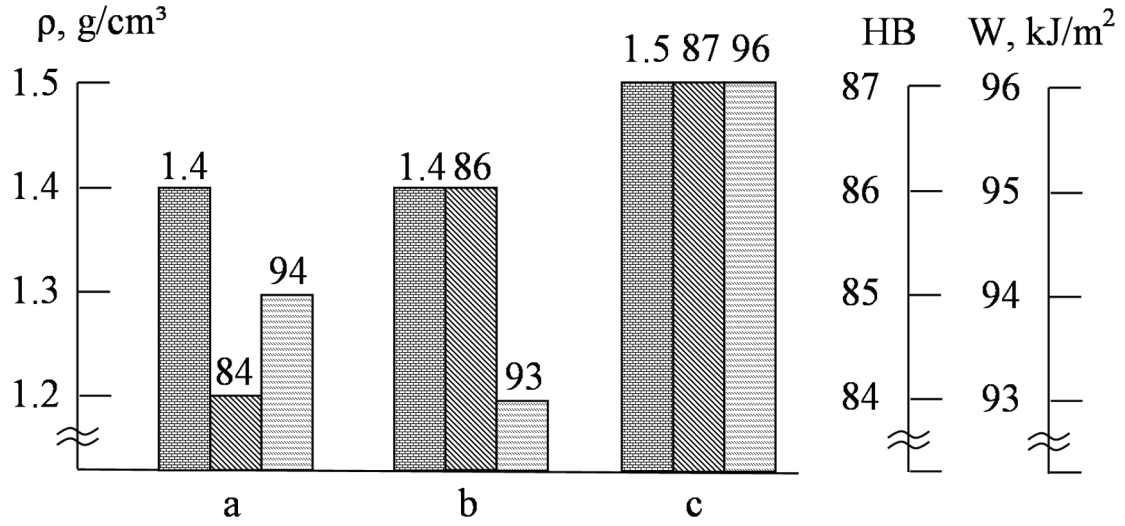


Fig. 1. Values of density (ρ), hardness (HB) and impact toughness (W) of CM based on epoxy matrix and fabrics of different nature: a) glass fabric; b) carbon fabric; c) basalt fabric.
▒ - density; ▨ - hardness; ▭ - impact toughness

ing nano- and microparticles used as a binder, regardless of their type.

At the initial stage of the experiment, the physical and mechanical properties of samples manufactured on the basis of an epoxy matrix and various fabric types were determined. Six types of fibrous fillers were used to create the samples. Fiber thickness is 9-11 μm. The samples were used in the form of fabrics formed from these fibers. Fabric thickness is 0.2 mm.

During the experiment, the influence of the type of fabric (fiberglass, carbon or basalt) on the physical and mechanical parameters of the composite material was revealed. A pattern of changes in material density depending on the reinforcing filler was established: glass (1.4 g/cm$^3$) and carbon (1.4 g/cm$^3$) fabrics give approximately the same value, whereas basalt fabric (1.5 g/cm$^3$) leads to a slightly higher density, which is associated with the higher density of the basalt fibers themselves (see Fig. 1). A similar trend is observed for Brinell hardness (HB): the composite with glass fabric has the lowest value (84), the carbon fiber composite has a higher value (86), and the basalt fiber composite has the highest value (87).This is explained by the increase in the resistance of the material surface to local indentation under the action of the indenter.

The maximum impact toughness (96 kJ/m$^2$) was recorded for the composite reinforced with basalt fabric. This value slightly exceeds those for materials with glass (94 kJ/m$^2$) and carbon (93 kJ/m$^2$) fillers, indicating a better ability of such a composite to absorb impact energy. In our opinion, the increase in impact strength occurs because the fabric fibers, having greater strength than the matrix, absorb the main impact load and prevent the propagation of through cracks.

Additionally, the cohesive characteristics of the obtained composites were studied. As shown in Fig. 2, the Young's modulus value increases from 22 GPa (for the sample with glass filler) to 25 GPa (for the composite based on basalt fabric). This indicates an increase in material stiffness when using stronger fibers. The composite reinforced with carbon fabric, in terms of elastic modulus (24 GPa), occupies an intermediate position among all tested samples, which suggests a favorable ratio of stiffness to low density for this material.

It has been experimentally confirmed (Fig. 2) that the fracture stresses of composites under bending loads also increase when replacing the type of reinforcing fibers: 514 MPa (composite with glass fabric), 526 MPa (with carbon fabric), 538 MPa (with basalt fabric). A similar pattern is observed when analyzing tensile test data: 380 MPa (with glass fabric), 402 MPa (with carbon fabric), 413 MPa (with basalt fabric). The obtained results demonstrate a comprehensive increase in the strength of composites (both in bending and tension), proving the possibility of using basalt fabrics to resist external mechanical influences.

The improvement in mechanical properties of composite materials reinforced with various fabric types (especially basalt) is due to the high tensile strength of these fibers and their

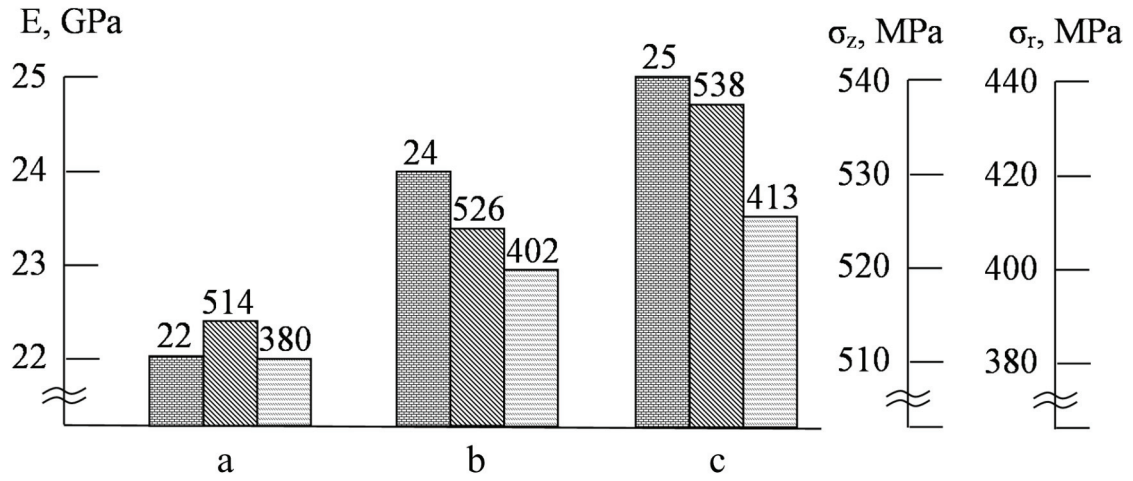


Fig. 2. Values of elastic modulus (E), flexural breaking stress ($\sigma_z$) and tensile breaking stress ($\sigma_r$) of CM based on epoxy matrix and fabrics of different nature: a) glass fabric; b) carbon fabric; c) basalt fabric. ▭ - elastic modulus; ▨ - flexural breaking stress; ▭ - tensile breaking stress.

enhanced adhesion to the epoxy matrix. The increase in adhesive interaction is associated with the presence of active functional groups on the surface of basalt fibers, which promotes the activation of interfacial contact with epoxy oligomer macromolecules during composite curing.

Composites reinforced with carbon and glass fabrics, demonstrating high hardness and elastic modulus values, ensure proper stability of operational properties over time, as well as resistance to deformation. At the same time, it is worth noting the balanced ratio of strength to cost for composites with these types of fillers.

The use of reinforcing textile materials in polymer composites, in particular basalt fabrics, makes it possible to significantly improve both the mechanical parameters (tensile and flexural strength) and the operational properties (hardness, impact resistance) of epoxy composites. The obtained data confirm the feasibility of using basalt and carbon fabrics to create high-strength and rigid composite products or protective coatings that must withstand significant loads and dynamic impacts.

Based on these results, basalt and carbon fabrics were chosen for further manufacturing of composite materials. Their bonding was carried out using an epoxy binder plasticized with an aliphatic oligomer.

As can be seen from the data presented in Figs. 3 and 4, the addition of aliphatic resin DEG-1 to the epoxy oligomer significantly increases the mechanical properties of the composites compared to the unmodified epoxy matrix (Figs. 1, 2). In particular, it was recorded that the density of composites with a plasticized matrix (Fig. 3) increases for both types of reinforcing fabrics: in the case of carbon filler – from 1.4 to 1.5 g/cm$^3$, and with basalt filler – from 1.5 to 1.6 g/cm$^3$. This is explained by the formation of a denser structural network of the polymer matrix. As for hardness, it remains practically unchanged: for samples with carbon fabric, the Shore hardness (HB) index did not change (86), and for composites based on basalt fabric, the hardness increased slightly – from 87 to 88, which indicates a slight increase in resistance to surface deformations.

The most significant increase was recorded for the parameter of impact resistance. In samples with carbon filler, this value rose from 93 to 98 kJ/m$^2$, while for basalt-based composites – from 96 to 112 kJ/m$^2$, which corresponds to an increase in resistance to dynamic impacts within the range of 14–17%.

Figure 4 demonstrates that as a result of plasticization of the binder, the elastic modulus increases: for carbon-containing composites – from 24 to 28 GPa, and for basalt-containing ones – from 25 to 31 GPa, which means an increase in stiffness characteristics by 16–24%. Furthermore, the values of ultimate bending stresses improved: from 526 to 578 MPa (carbon fabric) and from 538 to 592 MPa (basalt fabric). A similar positive trend was recorded for tensile strength – from 402 to 418 MPa and from 413 to 427 MPa, respectively. All this demonstrates a comprehensive strengthening of cohesive bonds within the composites.

The main reason for the improvement in properties due to plasticization is the reduction

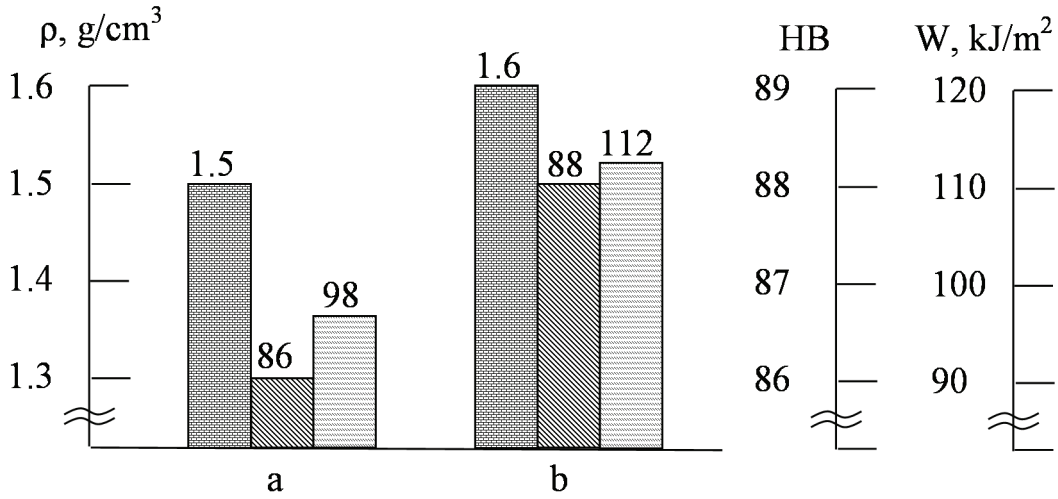


Fig. 3. Values of density (ρ), hardness (HB) and impact toughness (W) of CM based on epoxy matrix plasticized with aliphatic resin DEG-1 and fabrics of different nature: a) carbon fabric; b) basalt fabric.
▒ - density; ▨ - hardness; ▭ - impact toughness

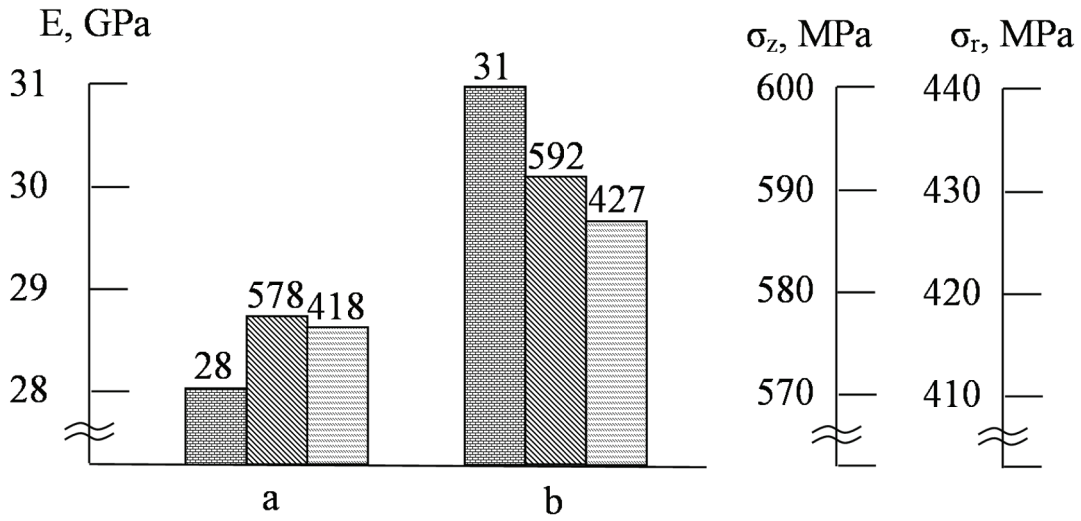


Fig. 4. Values of elastic modulus (E), flexural breaking stress ($\sigma_z$) and tensile breaking stress ($\sigma_r$) of CM based on epoxy matrix plasticized with aliphatic resin DEG-1 and fabrics of different nature: a) carbon fabric; b) basalt fabric.
▒ - elastic modulus; ▨ - flexural breaking stress; ▭ - tensile breaking stress.

of internal residual stresses in the polymer matrix and improvement of its deformability. As a result, the load is more evenly redistributed between the textile layers. It is worth emphasizing that the aliphatic resin plays the role of a plasticizer, which makes the polymer chains of the binder more mobile. This allows increasing the cohesive strength of the matrix.

If we compare the obtained data with previous measurements (Figs. 1 and 2), it becomes obvious: plasticization has made it possible to more fully realize the reinforcing potential of both types of fillers. For systems with carbon fabrics, the most pronounced increase was recorded for the elastic modulus (the absolute value increased by 16.6%), which is due to improved adhesive interaction between the fibers and the polymer matrix.

In the case of using basalt fabrics, the decisive factor was the increase in impact toughness (+16.5%). This is explained by the fact that the plasticized matrix better dampens and dissipates impact energy. In addition, plasticization reduces the concentration of residual stresses in the "fiber-matrix" contact zone, which prevents premature destruction of the material.

The synergistic mechanism deserves special attention: the plasticized binder deforms more easily, allowing forces to be transferred more effectively between adjacent layers of reinforc-

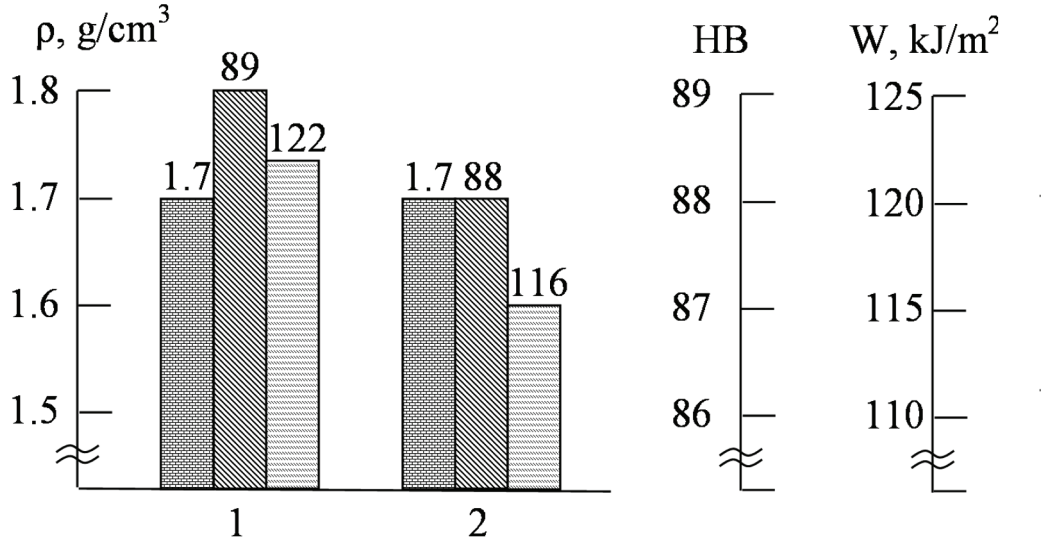


Fig. 5. Values of density (ρ), hardness (HB) and impact toughness (W) of CM based on epoxy matrix plasticized with aliphatic resin DEG-1 and fabric lay-up option (in layers): Configuration A: basalt fabric (2) + carbon fabric (2) + basalt fabric (2); Configuration B: carbon fabric (2) + basalt fabric (2) + carbon fabric (2).
▒ - density; ▨ - hardness; ▭ - impact toughnes

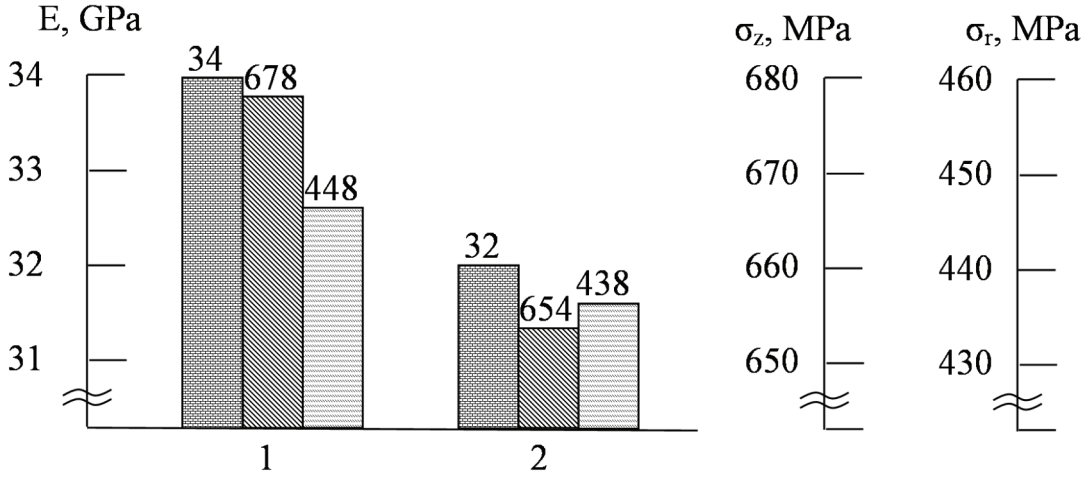


Fig. 6. Values of elastic modulus (E), flexural breaking stress ($\sigma_z$) and tensile breaking stress ($\sigma_r$) of CM based on epoxy matrix plasticized with aliphatic resin DEG-1 and fabric lay-up scheme (in layers): Configuration A: basalt fabric (2) + carbon fabric (2) + basalt fabric (2); Configuration B: carbon fabric (2) + basalt fabric (2) + carbon fabric (2).
▒ - elastic modulus; ▨ - flexural breaking stress; ▭ - tensile breaking stress

ing fabric, which, in turn, ensures the necessary rigidity and strength of the product. According to a comparative analysis of the two types of composites, materials containing basalt demonstrate a significantly higher increase in properties when using a plasticized binder – especially in terms of impact toughness and elastic modulus. Nevertheless, composites with carbon fabric, although inferior in absolute values of the studied characteristics, still remain of significant interest for further practical application.

Based on the above data, it can be concluded that the introduction of aliphatic resin DEG-1 into the epoxy binder is an effective way to improve the characteristics of reinforced polymer composites. Furthermore, the prospects of the combined use of basalt and carbon fabrics together with a polymer binder modified with a plasticizer have been experimentally confirmed. Therefore, in subsequent stages, composite materials were manufactured by alternating fabrics according to the following schemes:

Configuration A: basalt fabric – 2 layers → carbon fabric – 2 layers → basalt fabric – 2 layers;

Configuration B: carbon fabric – 2 layers → basalt fabric – 2 layers → carbon fabric – 2 layers.

Tests (see Figs. 5, 6) have shown that such layered arrangement of dissimilar fillers makes it possible to create high-strength hybrid composites. It was found that both options provide the same density of the final product – 1.7 g/cm$^3$, which indicates the reproducibility of the structure regardless of the layer order. Regarding hardness, there is a slight advantage of configuration A (89 conventional units) over configuration B (88 units), which is probably due to the higher level of crosslinking in the surface layer formed by the basalt sheet.

Analysis of impact toughness revealed a quite noticeable gap: for Scheme A, this parameter is 122 kJ/m$^2$, while for Scheme B it is only 116 kJ/m$^2$. This means that the first option significantly better dissipates energy under dynamic impacts.

From the data in Fig. 6, it can be seen that the elastic modulus is also higher in Option A – 34 GPa versus 32 GPa in Option B, which confirms the increased stiffness of products formed according to the first scheme. Flexural strength demonstrates a significant advantage of the same configuration: 678 MPa versus 654 MPa (an increase of 3.7%). A similar picture is observed for tensile breaking stress – 448 MPa versus 438 MPa in favor of Option A, indicating a general increase in strength parameters.

In our opinion, the improved properties of composites with alternating fibers are explained by the synergy of dissimilar fillers, whereby the weaknesses of some materials are compensated by the strengths of others.

In the first configuration, the outer layer (basalt) absorbs external loads and impacts, while the inner carbon layer is responsible for flexural and tensile strength. Together, this leads to an increase in the overall cohesive strength of the composite.

The second option, where the carbon fabric is on the outside (providing stiffness) and the basalt fabric is on the inside (providing toughness), proved to be less successful.

The difference in impact toughness (5.2% in favor of Scheme A) is due to the fact that basalt fibers more effectively absorb impact energy, so their location in the outer zone is optimal. The higher flexural strength values for the first scheme are explained by a more rational distribution of stresses – the layers that better resist bending (basalt) are located precisely in the zone of maximum forces. That is, the maximum tangential compressive and tensile stresses act on the surface and bottom of the sample, respectively. It is in these zones that basalt fabrics are located. The increase in the elastic modulus by 6.3% in variant A indicates better intermolecular interaction of heterogeneous tissues precisely in this order of alternation.

The obtained data convincingly prove that rational design of the layer sequence in multilayer composites is a key factor in achieving maximum operational performance. Consequently, Scheme A (basalt → carbon → basalt) is more appropriate for creating high-strength composites with improved mechanical characteristics.

As already noted earlier, to increase the performance indicators of polymer composites, it is advisable to add carbon nanotubes or finedispersed chromium oxide powder to the epoxy binder. The optimal concentrations of these modifiers in the matrix have been experimentally established as 0.05% and 15%, respectively [11, 16-18, 23-28]. Based on this, further tests were carried out on samples reinforced according to the first scheme, using a plasticized epoxy composition filled with these additives in optimal dosages.

In general, for samples modified with nanotubes or chromium oxide a significant increase in operational performance was recorded compared to the base version on a plasticized matrix (CM 1) – see Figs. 7 and 8. Thus, the density of the materials increased from 1.7 g/cm$^3$ (CM 1) to 1.9 g/cm$^3$ (CM 2) and 1.8 g/cm$^3$ (CM 3), which is explained by the introduction of additional solid fillers into the binder (Fig. 7). In addition, hardness increased from 89 (CM 1) to 93 units for both modified composites (CM 2 and CM 3).

Of particular note is the significant increase in impact toughness: from 122 kJ/m$^2$ (CM 1) to 184 kJ/m$^2$ (CM 2) and 156 kJ/m$^2$ (CM 3), which corresponds to an increase of 50.7% and 27.8%, respectively.

Additionally, an improvement in cohesive strength was recorded in materials based on dispersion-filled reinforced composites. In particular, when using dispersed powders, the elastic modulus increases from 34 GPa (CM 1) to 46 GPa (CM 2) and 42 GPa (CM 3), which means an increase in stiffness by 35.2% and 23.4%, respectively (Fig. 8). Flexural breaking stress increases from 678 MPa (CM 1) to 842 MPa (CM 2) and 736 MPa (CM 3) – i.e., by 24.1% and 8.4%, respectively. Tensile strength values also demonstrate positive dynamics: from 448

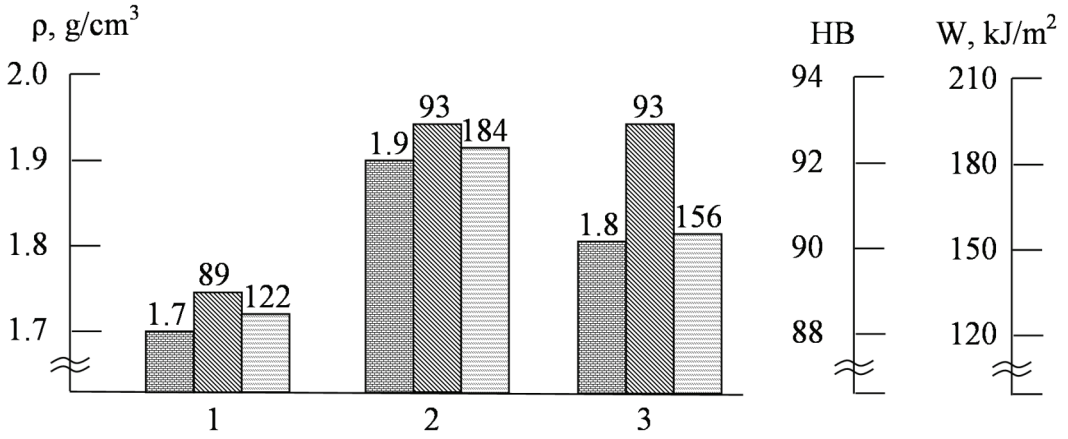


Fig. 7. Values of density (ρ), hardness (HB) and impact toughness (W) of CM formed according to fabric lay-up configuration A (Fig. 6): 1 – CM 1 based on epoxy matrix plasticized with aliphatic resin DEG-1; 2 – CM 2 based on plasticized matrix and nanotubes (0.05 %); 3 – CM 3 based on plasticized matrix and chromium oxide (15 %). ▒ - density; ▨ - hardness; ▤ - impact toughnes

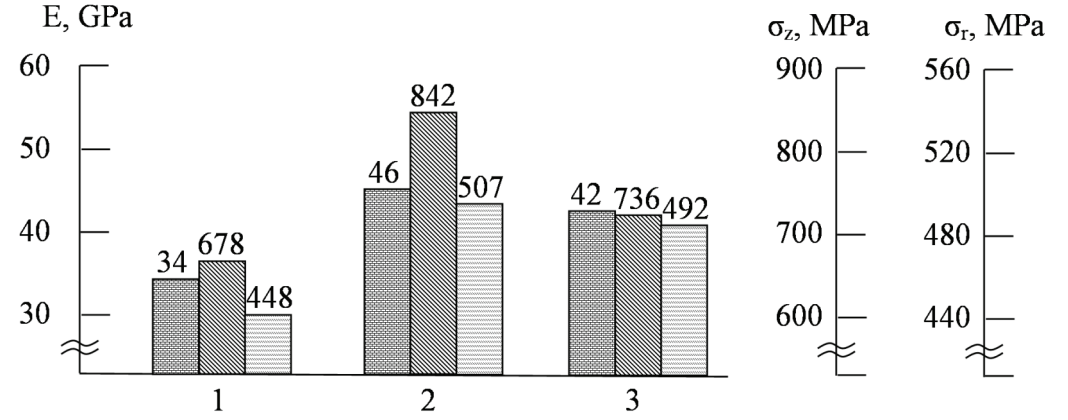


**Fig. 8.** Values of elastic modulus (E), flexural breaking stress ($\sigma_z$) and tensile breaking stress ($\sigma_r$) of CM formed according to fabric lay-up configuration A (Fig. 6): 1 – CM 1 based on epoxy matrix plasticized with aliphatic resin DEG-1; 2 – CM 2 based on plasticized matrix and nanotubes (0.05 %); 3 – CM 3 based on plasticized matrix and chromium oxide (15 %).
▒ - elastic modulus; ▨ - flexural breaking stress; ▤ - tensile breaking stress..

MPa (CM 1) to 507 MPa (CM 2) and 492 MPa (CM 3), giving an increase of 13.1% and 9.7%.

The positive effect of nanotubes on the mechanics of composites is due to their ability to form a developed three-dimensional reinforcing network inside the polymer matrix, which significantly increases stiffness and strength. In this case, the nanotubes act as so-called "bridges" between individual layers, effectively blocking crack propagation, which has a particularly positive effect on impact toughness. As for chromium oxide, its positive role is associated with an increase in the hardness of the polymer material due to improved adhesion to the fabric layers.

It should be noted that nanotubes turned out to be significantly more effective than chromium oxide. In our opinion, this is explained by their high length-to-diameter ratio and their own high strength characteristics. This makes it possible to create a more perfect matrix structure during polymerization, which acts as a binding link. Based on the totality of all studied parameters, the advantage of nanotubes is obvious for the formation of hybrid composites intended for operation under severe conditions. Thus, the modification of the plasticized epoxy matrix with nanotubes is an effective tool for significantly improving the mechanical characteristics of composite materials for the transportation industry.

It is known [5, 17, 28] that the thickness of protective layers significantly affects their properties, including mechanical ones. There-

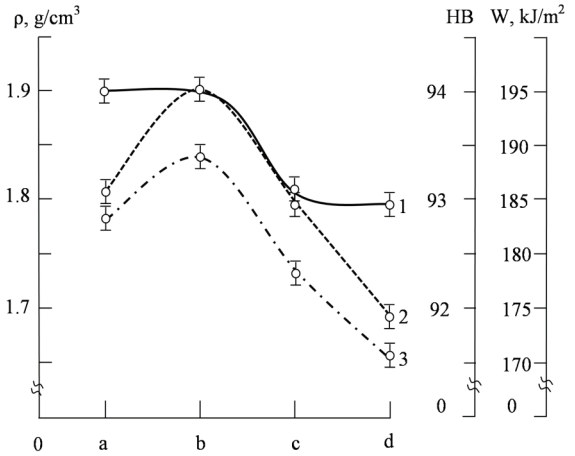


Fig. 9. Dependence of density (1), hardness (2) and impact toughness (3) of CM formed on the basis of plasticized epoxy matrix and nanotubes, on the number of fabric layers formed according to lay-up schemes: a) 6 layers: basalt fabric (2) + carbon fabric (2) + basalt fabric (2); b) 8 layers: basalt fabric (3) + carbon fabric (2) + basalt fabric (3); c) 10 layers: basalt fabric (3) + carbon fabric (4) + basalt fabric (3); d) 12 layers: basalt fabric (4) + carbon fabric (4) + basalt fabric (4).

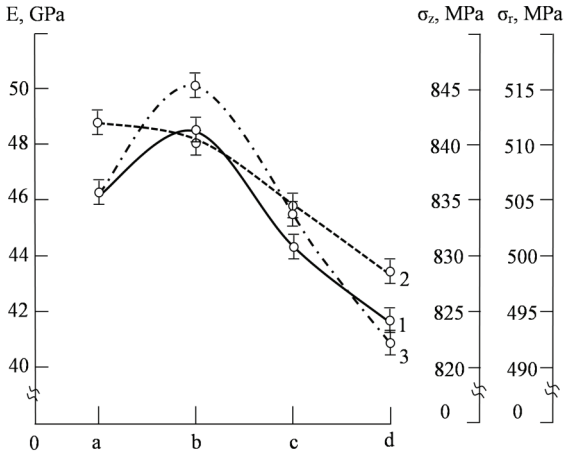


Fig. 10. Dependence of elastic modulus (1), flexural breaking stress (2) and tensile breaking stress (3) of CM formed on the basis of plasticized epoxy matrix and nanotubes, on the number of fabric layers formed according to lay-up schemes: a) 6 layers: basalt fabric (2) + carbon fabric (2) + basalt fabric (2); b) 8 layers: basalt fabric (3) + carbon fabric (2) + basalt fabric (3); c) 10 layers: basalt fabric (3) + carbon fabric (4) + basalt fabric (3); d) 12 layers: basalt fabric (4) + carbon fabric (4) + basalt fabric (4).

fore, this study investigated the dependence of the characteristics of hybrid composites on the number of reinforcing layers – from 6 to 12. Tests of variants (*a, b, c, d*) with different numbers of layers (6, 8, 10, 12) revealed a clear relationship between physical-mechanical parameters and thickness (Figs. 9, 10). In particular, the density of the materials is 1.9 g/cm$^3$ (options *a* and *b* – 6 and 8 layers) and 1.8 g/cm$^3$ (options *c, d* – 10 and 12 layers), which indicates the optimal density of the structure for samples *a* and *b* (Fig. 9). The highest hardness value (94) was recorded for the eight-layer composite (option *b*); with a further increase in thickness, this indicator decreases to 92–93 units, indicating maximum resistance to deformation in the medium thickness range. Impact toughness reaches its peak (188 kJ/m$^2$) also for the eight-layer sample (option *b*), which is 2.2% higher than the six-layer sample (184 kJ/m$^2$) and 5.7–8.5% higher than the indicators for 10–12 layers.

Analysis of the dependence of the elastic modulus on the number of layers (Fig. 10) revealed a maximum (48 GPa) for eight-layer composites. With a further increase in the number of layers, a decrease in this parameter to 42–44 GPa is observed for samples with 10–12 layers, which confirms the loss of stiffness with excessive increase in the thickness of the hybrid material.

Flexural strength gradually decreases from 842 MPa (six-layer sample) to 828 MPa (12-layer composite), which means a decrease of approximately 1.7% for every two additional layers. Tensile strength also has a maximum (515 MPa) for eight-layer samples, after which it decreases to 493–500 MPa when moving to 10–12 layers, confirming the optimality of the medium thickness range.

The improvement in the properties of hybrid composites containing 6–8 layers is due to the achievement of a balance between the reinforcing effect of the fabrics and the ability of the matrix to uniformly distribute the load. When the thickness exceeds 8 layers, the probability of accumulation of interlayer defects increases, which increases the risk of delamination. Consequently, this leads to a deterioration in the mechanical characteristics of the developed materials.

It can be argued that the eight-layer variant demonstrates the best balance of properties due to a sufficient number of reinforcing layers while maintaining high interlayer adhesion. This, in turn, determines the cohesive properties of the composite as a whole.

Comparison of options *a* (6 layers) and *b* (8 layers) shows the advantage of the latter in terms of most absolute indicators – especially in terms of impact toughness and elastic modulus. A further increase in the number of layers (options *c, d*) reduces the reinforcement efficiency

due to the occurrence of structural defects and an increased risk of delamination.

Thus, the analysis of the "property-thickness" relationship revealed a clear optimum in the range of 6–8 layers, where the best combination of cohesive strength and deformation characteristics is observed. For practical application, this range is recommended as technologically optimal, ensuring high physical and mechanical properties without significantly complicating the production process.

## *4. Conclusions*

1. It has been experimentally confirmed that the use of reinforcing materials in hybrid epoxy composites provides a significant increase in their mechanical parameters. Thus, the use of basalt fabric made it possible to increase the ultimate flexural strength from 514 MPa (for the sample with glass fabric) to 538 MPa, and impact toughness – from 94 to 96 kJ/m². The positive effect of basalt fabrics compared to other types of fillers is explained by their high tensile strength and enhanced adhesion to the epoxy matrix. The increase in adhesive interaction, in turn, is due to the presence of active functional chemical groups on the surface of basalt fibers, which stimulate interfacial contact with epoxy oligomer macromolecules during the crosslinking of the composite.

2. It has been proven that the introduction of aliphatic resin DEG-1 in an amount of 12% into the epoxy resin ED-20 (100%) makes it possible to significantly increase the mechanical properties of reinforced composites due to the plasticization effect. After modification of the binder, the elastic modulus increased: for materials with carbon filler – from 24 to 28 GPa, and for basalt-containing samples – from 25 to 31 GPa, which corresponds to an increase in stiffness within the range of 16–24%. In addition, the values of flexural strength increased: from 526 to 578 MPa (carbon fabric) and from 538 to 592 MPa (basalt fabric). A similar positive trend was recorded for tensile strength: for carbon-containing composites – from 402 to 418 MPa, for basalt-containing ones – from 413 to 427 MPa. All this demonstrates a comprehensive increase in the number of cohesive bonds within the materials.

The mechanism of the synergistic effect is that the plasticized binder is more easily deformed, whereby the forces are more evenly redistributed between adjacent layers of fabrics, while the fabrics themselves provide the necessary stiffness and strength. A comparative analysis of the two types of fillers shows that the properties of basalt composites are significantly improved when using a plasticized binder – especially in terms of impact toughness and elastic modulus. Nevertheless, materials based on carbon fabric, although having somewhat lower absolute values of the studied mechanical parameters, also possess significant potential for practical application.

3. It has been shown that the alternation of dissimilar tissues creates a synergistic effect that contributes to improving the characteristics of hybrid composites. The hybrid structure of the "basalt–carbon–basalt" type provides a flexural strength of 678 MPa and an elastic modulus of 34 GPa. This is explained by the rational distribution of stresses across the thickness of the material: the outer basalt layers effectively withstand bending loads, while the inner carbon layer is responsible for high tensile strength.

4. It has been established that the addition of carbon nanotubes at a concentration of 0.05% to the plasticized matrix makes it possible to significantly improve the operational characteristics. Compared to a hybrid composite based solely on a plasticized binder, the introduction of nanotubes provides an increase in the elastic modulus from 34 to 46 GPa, and an increase in impact toughness from 122 to 184 kJ/m². The reason for this increase in properties lies in the formation of a spatial reinforcing structure consisting of nanotubes within the polymer binder. This network acts as an effective barrier to crack propagation and simultaneously increases the energy-absorbing capacity of the material.

5. It has been established that the number of reinforcing layers significantly affects the mechanical characteristics of the composites. The best results were achieved in the manufacture of hybrid samples containing 6 to 8 layers: the elastic modulus was 46–48 GPa, and the impact toughness was 184–188 kJ/m². The improvement in performance in this thickness range is explained by achieving an optimal balance between the reinforcing contribution of the fabrics and the ability of the matrix to evenly redistribute forces without the formation of internal structural inhomogeneities.

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