Effect of layer number, orientation, and weave type of aramid fabric on the impact penetration resistance of epoxy composites

Kamil Czech[1), 2), *)] (ORCID ID: 0000-0003-3712-697X), **Mariusz Oleksy**[1)] (0000-0001-5515-8575)

DOI: https://doi.org/10.14314/polimery.2025.7.2

Abstract: This study presents the effect of the number of layers, fiber orientation, and fabric weaves on the impact penetration resistance of epoxy composites reinforced with aramid fabrics. Composites containing 4, 8, and 12 layers were fabricated, with both oriented and non-oriented reinforcement, using two types of weaves. The best results were achieved by laminates with oriented reinforcement and/or twill weave. Increasing the number of layers, applying orientation, and using twill weave improved resistance to penetration impact using the drop-weight method.

Keywords: aramid fabric, epoxy composites, drop-weight, fiber orientation, weave type.

Wpływ liczby warstw, orientacji oraz rodzaju splotu tkaniny aramidowej na odporność kompozytu epoksydowego na przebicie udarowe

Streszczenie: W pracy przedstawiono wpływ liczby warstw, orientacji oraz rodzaju splotu tkaniny aramidowej na odporność kompozytów epoksydowych na przebicie udarowe. Otrzymano kompozyty zawierające 4, 8 i 12 warstw o zorientowanym i niezorientowanym wzmocnieniu oraz dwóch splotach. Najlepsze wyniki uzyskano w przypadku laminatów ze zorientowanym wzmocnieniem i/lub splotem skośnym. Większa liczba warstw, orientacja i splot skośny poprawiały odporność na przebicie udarowe metodą spadającego grotu.

Słowa kluczowe: kompozyty epoksydowe, tkanina aramidowa, test spadającego grotu, orientacja włókien, rodzaj splotu.

In recent decades, there has been rapid development in fiber-reinforced composites, particularly in applications requiring high mechanical strength combined with low weight. One of the key areas of their use is ballistic protection systems and impact-resistant structures, where a material's resistance to penetration is of critical importance. Among the reinforcing materials, aramid fabrics such as Kevlar® occupy a prominent position due to their high tensile strength, chemical resistance, and favorable strength-to-weight ratio [1–3]. When combined with a polymer matrix – most commonly based on epoxy resins – they form composites with excellent mechanical performance [4]. Aramid-reinforced composites are now considered the primary material of choice for protective components in the defense industry. They are widely used in ballistic helmets, bulletproof vests, and lightweight armor panels for military vehicles [5–7]. Their combination of high energy absorption capacity, low weight, and environmental durability has made them the gold standard in passive protection systems [8].

However, the mechanical performance of aramid composites strongly depends on several structural factors, including the number of layers, fiber orientation, and fabric weave type [9, 10]. Increasing the number of reinforcing layers typically enhances penetration resistance and structural stiffness. At the same time, it leads to higher weight, which may be a limiting factor in mobile applications such as body armor or vehicle components [11–13].

The orientation of individual fabric layers also significantly affects the material's behavior under impact loading. In fiber-reinforced composites, the reinforcement – here, aramid fabric – is primarily responsible for transferring mechanical loads, including impact energy. In a simple arrangement where fibers are oriented only at 0° and 90°, energy is transferred mainly along the X and Y axes, i.e., the principal fiber directions [14, 15]. While such configurations are effective under aligned loads, they may offer limited resistance to off-axis or randomly directed impacts. To enhance the ability of the composite to dissipate impact energy in multiple directions, multi-axial fiber orientations are commonly used–

1) Department of Polymer Composites, Faculty of Chemistry, Rzeszow University of Technology, al. Powstańców Warszawy 6, 35-959 Rzeszów, Poland.

2) Doctoral School of the Rzeszow University of Technology, al. Powstańców Warszawy 12, 35-959 Rzeszów, Poland.

*) Author for correspondence: k.czech@prz.edu.pl

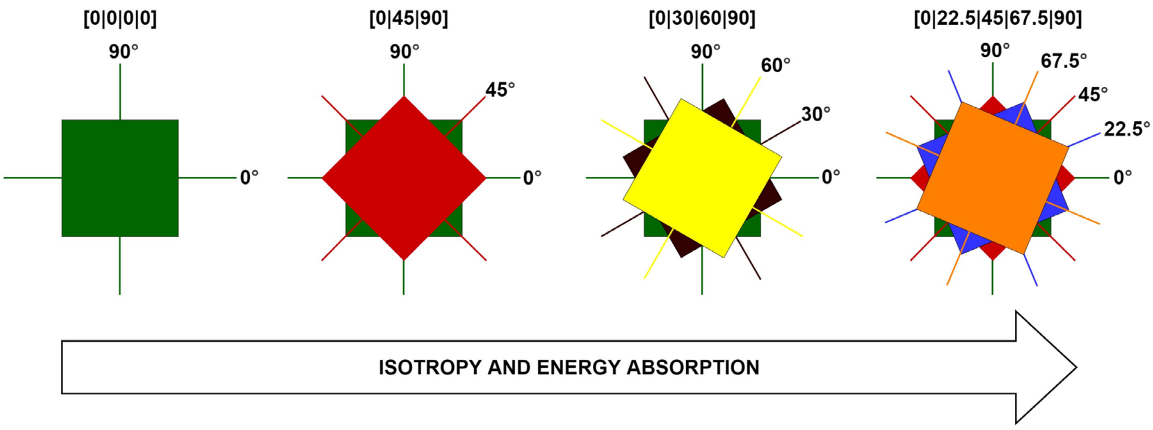


Fig. 1. Examples of reinforcement fabric orientation [20]

such as ±45°, 0°/60°/120°, or hybrid arrangements involving several angles [16, 17]. These layups help achieve quasi-isotropic mechanical behavior within the laminate plane, facilitating more uniform and effective propagation of the impact wave. As a result, the energy is gradually absorbed by successive layers along different fiber paths, which reduces localized stress concentrations and increases overall penetration resistance [18, 19]. Examples of the used fiber layer orientations are illustrated in Fig. 1.

The weave type of the aramid fabric plays an important role in load transfer and in the failure mechanisms of the composite [21]. Simple weaves, such as plain weaves, offer dimensional stability and compact structure, whereas more complex patterns, such as twill or satin, allow for better conformability and enhance the material's ability to absorb impact energy. They facilitate controlled energy dissipation through sequential, progressive damage of the composite structure [22–24].

Although the literature includes many studies on the mechanical behavior of aramid composites [25–29], there is still a lack of comprehensive data on the combined effects of structural parameters on impact penetration resistance, particularly under drop-weight test conditions. These tests simulate real-world dynamic impacts and provide valuable insights into the performance of engineered composite structures [7, 30].

The aim of this study was to investigate the effect of the number of layers, orientation, and weave type of aramid fabric on the impact penetration resistance of epoxy composites using the drop-weight method. The results of this investigation may serve as a basis for optimizing the structure of laminates used in protective systems.

EXPERIMENTAL PART

Materials

The epoxy resin used in this study was Epidian 624, with a density of 1.11 g/cm³ and an epoxy number ranging from 0.485 to 0.51 mol/100 g. The curing agent was Z1 hardener, both components supplied by Ciech Sarzyna S.A. (Nowa Sarzyna, Poland). The reinforcement consisted of aramid fabrics supplied by Rymatex Ltd (Rymanów, Poland). Two types of aramid fabric were used: a plain weave with a grammage of 220 g/m² and a twill weave with a grammage of 300 g/m².

Composite fabrication

Composite laminates containing 4, 8, and 12 layers of aramid fabric were manufactured using the resin infusion technique. The appropriately arranged reinforcement layers were impregnated with an epoxy system consisting of Epidian 624 resin and Z1 hardener, mixed in a weight ratio of 100:13. A detailed description of the layer configurations and sample designations is provided in Tab. 1.

The warp and weft yarns forming the fabric structure were oriented in subsequent layers at the following angles relative to the specimen axis: 0°/90° (layer 1), 22.5°/112.5° (layer 2), 45°/135° (layer 3), and 67.5°/157.5° (layer 4). These four layers formed a complete orientation package. For laminates containing 8 or 12 layers, two or three repetitions of this layup were used, respectively. From the cured laminates, square specimens measuring 100 × 100 mm were cut using a three-axis CNC milling

T a b l e. 1. Composites characteristics

Designation	Fabric layers	Weave type	Fabric orientation
P4	4	Plain	Lack
P8	8		
P12	12		
T4	4	Twill	
T8	8		
T12	12		
PO4	4	Plain	Contains
PO8	8		
PO12	12		
TO4	4	Twill	
TO8	8		
TO12	12		

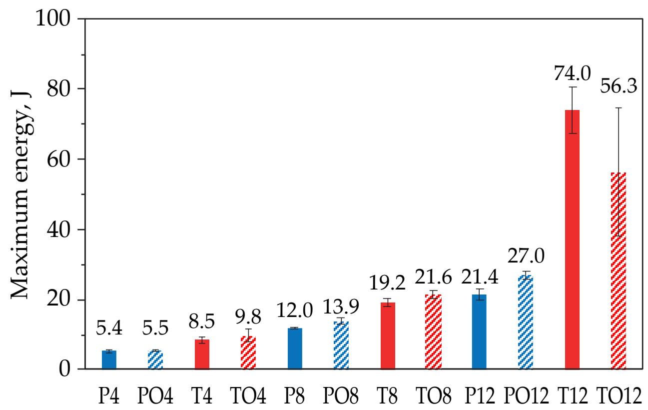


Fig. 2. Maximum energy for the tested composites

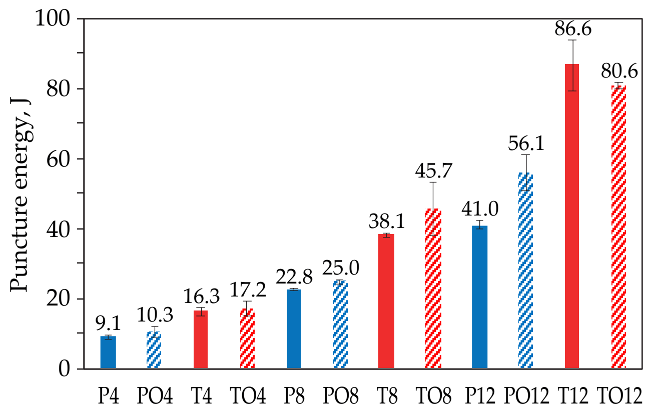


Fig. 3. Puncture energy for the tested composites

machine. These samples were subjected to impact penetration tests using the drop-weight method.

Methods

Five specimens of each type of fabricated composite were subjected to impact penetration testing using the drop-weight method. The impact tests (point loading) were carried out using a drop tower designed by Proximo Areo Ltd. (Rzeszów, Poland), in accordance with the PN-EN ISO 6603-2 standard. A 16 kg weight was dropped onto the specimens from a height of 1 meter, reaching an impact velocity of approximately 4.4 m/s. A hemispherical arrowhead with a diameter of 20 mm was used to apply the point load to the specimen surface.

RESULTS AND DISCUSSION

Similar trends were observed for both the maximum energy values (Fig. 2) and the puncture energy (Fig. 3). As the number of reinforcement layers increased, the values of both parameters rose for the tested composites. The highest maximum energy (E_m = 73.97 J) and puncture energy (E_p = 86.59 J) were achieved by the T12 laminate, while the lowest values were obtained for the P4 laminate, 5.38 J and 9.08 J, respectively.

Composites with oriented reinforcement exhibited higher values of maximum and puncture energies compared to their non-oriented counterparts, except for the T12 laminate, whose energy values exceeded those of TO12. Regarding the effect of fabric weaving, it was observed that laminates reinforced with non-oriented twill weaving fabric showed higher maximum and puncture energy values than those reinforced with non-oriented plain weaving fabric. The same trend was observed for laminates with oriented reinforcement, where weave outperformed plain weaves in terms of both energy values.

Similar tendencies were noted for the absorbed energy (Fig. 4). The amount of absorbed energy impact increased with the number of reinforcement layers. The highest absorbed energy (E_a = 75.48 J) was recorded for the TO12 laminate, while the lowest (5.09 J) corresponded to the P4 laminate. The absorbed energy values for composites with oriented reinforcement were higher than their non-oriented counterparts, except for the T4 laminate, which showed a slightly higher energy than TO4. Furthermore, laminates reinforced with twill weave fabric, both oriented and non-oriented, exhibited higher absorbed energy values compared to those reinforced with plain weaving fabric.

Fig. 5 shows the relative percentage change in the energy for the tested composites. In the analysis, the P4 laminate (a 4-layer composite with non-oriented reinforcement and plain weave) was adopted as the reference specimen. For all other variants, the relative percentage changes in maximum energy, puncture energy, and absorbed energy were calculated with respect to P4.

The results showed that each structural modification (increasing the number of layers, applying fiber orientation, and changing the weave to twill) contributed to a clear improvement in the impact penetration resistance of the composites. Particularly significant increases were observed for absorbed energy, confirming its key role in the design of protective structures. For the most advanced laminate configuration, TO12 (12 layers, oriented fibers, twill weave), the relative increases in E_m, E_p, and E_a were 945.8%, 787.2%, and 1382.7%, respectively. In turn, for laminate T12 (also 12 layers, but with non-oriented fibers), the respective values were 1273.7%, 853.6%, and 1352.8%.

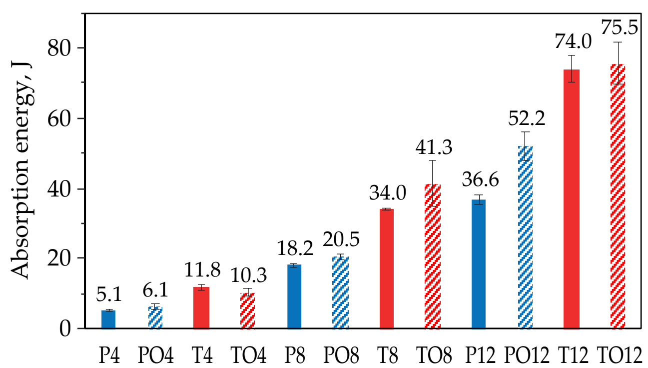
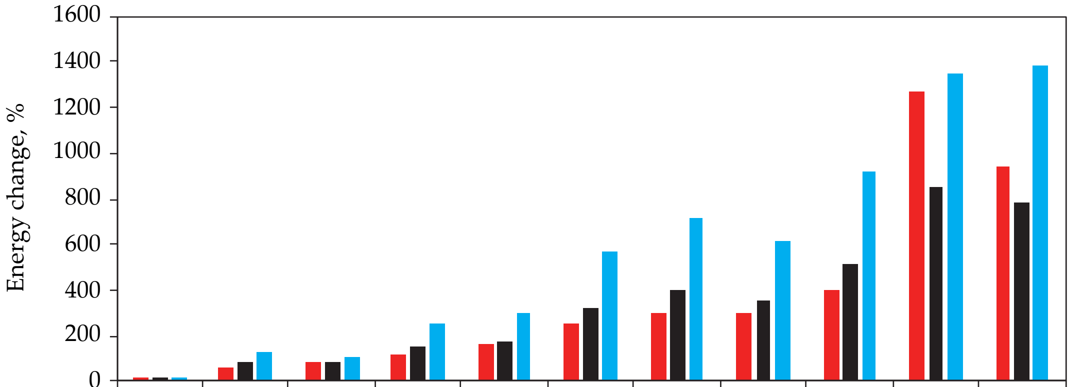


Fig. 4. Absorption energy for the tested composites



	PO	T4	TO4	P8	PO8	T8	TO8	P12	PO12	T12	TO12
ΔE_m	1.8	57.8	81.8	123.5	158.6	256.2	300.3	298.1	401.4	1273.7	945.8
ΔE_p	13.8	79.9	88.9	151.4	175.5	319.6	403.1	351.1	518.1	853.6	787.2
ΔE_a	20.4	132.1	102.1	257.3	302.3	568.5	711.9	619.8	924.7	1352.8	1382.7

Fig. 5. Percentage energy change of P4 composite

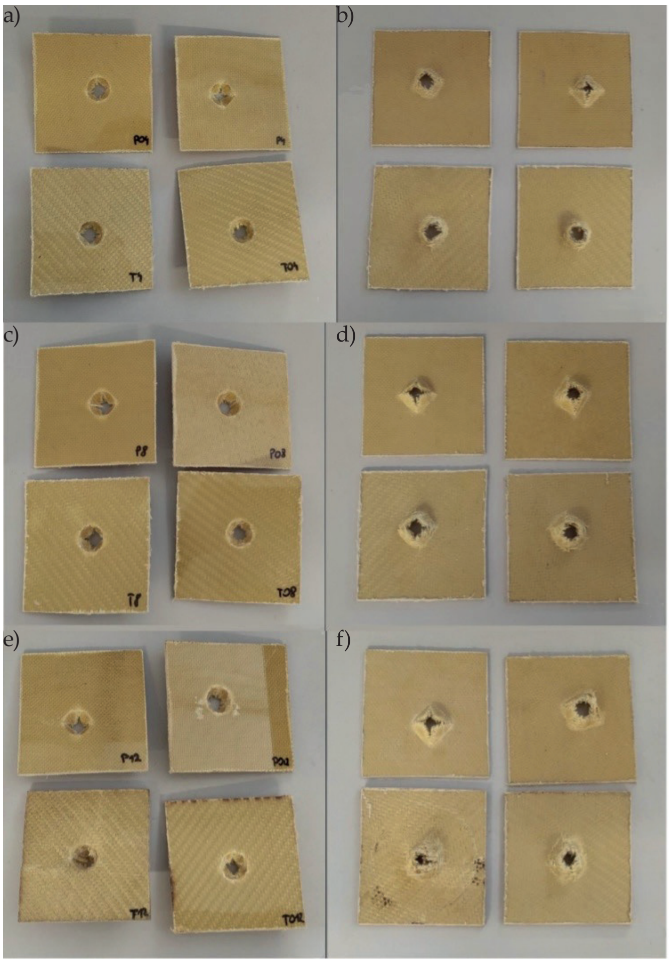


Fig. 6. Appearance of composite with 4, 8, and 12 layers, respectively, from the impact side (a, c, e) and the back side (b, d, f)

An increase in the number of layers led to a gradual rise in all energy values, while fiber orientation resulted in absorbed energy increases of up to 100–300% compared to non-oriented layouts (e.g., TO8 vs. T8: +143.4%). The weave type also had a significant influence–for instance, the PO12 laminate showed a 924.7% increase in E_a, while the P12 laminate showed a 619.8% increase.

Fig. 6 shows the appearance of the specimens after the impact penetration test. Figure also shows the complete perforation in the specimens caused by the impactor. A characteristic difference in perforation shape, consistent with the literature [31], was observed. Laminates with non-oriented fiber arrangements displayed a perforation shape resembling a regular tetrahedron, whereas those with oriented fibers exhibited a conical shape. This phenomenon is related to energy dissipation along the fibers forming fabric reinforcement. Fiber orientation leads to quasi-isotropic stress distribution in all directions corresponding to the warp and weft yarn orientations.

CONCLUSIONS

Increasing the number of aramid fabric layers in epoxy composites significantly improved their impact penetration resistance, as confirmed by the rising of maximum energy, puncture energy, and absorbed energy. Fiber orientation within the layers also played a crucial role in the mechanical properties of the composites – oriented reinforcement facilitated more efficient impact energy dissipation, resulting in higher penetration resistance for most tested composites. The type of fabric weave also influenced the results – laminates reinforced with twill weave fabric demonstrated better strength properties in terms of penetration and absorption energies compared to those with plain weave, regardless of fiber orientation.

Additionally, the shape of the perforation after impact penetration was closely related to fiber orientation – non-oriented layers exhibited perforations resembling a regular tetrahedron, whereas oriented layers produced conical perforations, reflecting different mechanisms of impact energy dissipation. The obtained results confirmed that the appropriate selection of the number of layers, fiber orientation, and fabric weave type enabled effective optimization of composite structures for improved impact penetration resistance using the drop-weight method.

Authors contribution

K.C. – conceptualization, methodology, writing-original draft, investigation, visualization, formal analysis, validation; M.O. – conceptualization, supervision, writing-review, and editing.

Funding

The research received no external funding.

Conflict of interest

The authors declare no conflict of interest.

REFERENCES

[1] Yao Y., Zhu D., Zhang H. *et al*.: *Journal of Materials in Civil Engineering* **2016**, *28(9)*, 04016081. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001587
[2] Luo J., Wen Y., Jia X. *et al*.: *Nature Communications* **2023**, *14*, 3019. https://doi.org/10.1038/s41467-023-38701-4
[3] Rao H.R., Bandhu D., Bhadauria A. *et al*.: *Composites: Mechanics, Computations, Applications: An International Journal* **2025**, *16(1)*, 51. https://doi.org/10.1615/CompMechComputApplIntJ.2024053127
[4] Murčinková Z., Postawa P., Winczek J.: *Polymers* **2022**, *14(15)*, 3060. https://doi.org/10.3390/polym14153060
[5] Gore P.M., Kandasubramanian B.: *Industrial and Engineering Chemistry Research* **2018**, *57(49)*, 16537. https://doi.org/10.1021/acs.iecr.8b04903
[6] de Castro Monsores K.G., Weber R.P., Monteiro S.N.: *Materials Science Forum* **2020**, *1012*, 43. https://doi.org/10.4028/www.scientific.net/MSF.1012.43
[7] Czech K., Oleksy M., Oliwa R. *et al*.: *Polimery* **2022**, *67(11-12)*, 552. https://doi.org/10.14314/polimery.2022.11.2
[8] Bao J., Wang Y., An R. *et al*.: *Defence Technology* **2022**, *18(10)*, 1822. https://doi.org/10.1016/j.dt.2021.09.009
[9] Sujon A.S., Habib M.A., Abedin M.Z.: *Journal of Materials Research and Technology* **2020**, *9(5)*, 10970. https://doi.org/10.1016/j.jmrt.2020.07.079
[10] Rajesh M., Singh S.P., Pitchaimani J.: *Journal of Industrial Textiles* **2018**, *47(5)*, 938. https://doi.org/10.1177/1528083716679157
[11] Öztoprak N., Özdemir O., Kandaş H.: *Journal of Composite Materials* **2021**, *56(3)*, 359. https://doi.org/10.1177/00219983211049290
[12] Fayed A.I.H., Amaim Y.A.A.E., Ramy O. *et al*.: *Research Journal of Textile and Apparel* **2021**, *27(1)*, 1. https://doi.org/10.1108/RJTA-03-2021-0027
[13] Stopforth R., Adali S.: *Defence Technology* **2019**, *15(2)*, 186. https://doi.org/10.1016/j.dt.2018.08.006
[14] Jiang L., Zhou Y., Jin F.: *Polymer Composites* **2022**, *43(8)*, 4835. https://doi.org/10.1002/pc.26817
[15] Biradar A., Arulvel S., Kandasamy J.: *International Journal of Impact Engineering* **2023**, *180*, 104700. https://doi.org/10.1016/j.ijimpeng.2023.104700
[16] Giasin K., Dhakal H.N., Featheroson C.A. *et al*.: *Polymers* **2022**, *14(1)*, 95. https://doi.org/10.3390/polym14010095
[17] Alagumalai V., Shanmugam V., Balasubramanian N.K. *et al*.: *Polymers* **2021**, *13(16)*, 2591. https://doi.org/10.3390/polym13162591
[18] Mawkhlieng U., Majumdar A., Laha A.: *RSC Advances* **2020**, *10*, 1066. https://doi.org/10.1039/C9RA06447H
[19] Hazzard M.K., Hallett S., Curtis P.T. *et al*.: *International Journal of Impact Engineering* **2017**, *100*, 35. https://doi.org/10.1016/j.ijimpeng.2016.10.007
[20] Czech K., Oliwa R., Krajewski D. *et al*.: *Materials* **2021**, *14(11)*, 3047. https://doi.org/10.3390/ma14113047
[21] Abtew M.A., Boussu F., Bruniaux P. *et al*.: *Composite Structures* **2019**, *223*, 110966. https://doi.org/10.1016/j.compstruct.2019.110966
[22] Zhou G., Sun Q., Meng Z. *et al*.: *Composite Structures* **2021**, *257*, 113366. https://doi.org/10.1016/j.compstruct.2020.113366
[23] Shaker K., Abbas A., Nawab Y. *et al*.: *Journal of Engineered Fibers and Fabrics* **2024**, *19*. https://doi.org/10.1177/15589250241230767
[24] Begum M.S., Milašius R.: *Fibers* **2022**, *10(9)*, 74. https://doi.org/10.3390/fib10090074
[25] Dharmavarapu P., Reddy M.B.S.: *Emergent Materials* **2022**, *5*, 1561. https://doi.org/10.1007/s42247-021-00246-x
[26] Yermakhanova A.M., Baiserikov B.M., Kenzhegulov A.K. *et al*.: *Journal of Elastomers and Plastics* **2023**, *55(2)*, 331.

https://doi.org/10.1177/00952443221147645
[27] Adekunle F., Seyam A.-F.M.: *Journal of Composites Science* **2025**, *9(3)*, 141. https://doi.org/10.3390/jcs9030141
[28] Bunea M., Bria V., Silva F.S. *et al.*: *Applied Composite Materials* **2021**, *28*, 1277. https://doi.org/10.1007/s10443-021-09910-1
[29] Abtew M.A., Boussu F., Bruniaux P. *et al.*: *Journal of Industrial Textiles* **2021**, *50(9)*, 1351. https://doi.org/10.1177/1528083719862883
[30] Czech K., Oleksy M.: *Measurement* **2024**, *230*, 114499. https://doi.org/10.1016/j.measurement.2024.114499
[31] Arora S., Majumdar A., Butola B.S.: *Composite Structures* **2020**, *233*, 111720. https://doi.org/10.1016/j.compstruct.2019.111720

Received 24 V 2025.
Accepted 14 VI 2025.