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Strength tests of polymer-glass composite to evaluate its operational suitability for ballistic shield plates

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Highlights

- Tensile characteristics of the composite are dependent on the specimen orientation.
- The total strain energy during tension is related to the reinforcement quantity.
- Degradation mechanism is associated strongly with a number of the reinforcing layers.
- Mechanical properties of the composite are depend on the fabrication conditions.

Abstract

The paper concerns the study of polymer-glass composite under tensile loading in order to determine changes in the tensile characteristics. Mechanical properties and features of damage zones important for operation and assessment of the technical conditions of the components made of this material are considered. Selected details of the experimental technique used are presented. The tensile characteristics of the polymer-glass composite are given. They were determined using specimens taken from various directions, with the main focus on the Young's modulus, elastic limit, yield point and ultimate tensile strength. An influence of the number of reinforcement layers, percentage content of the glass fibres as well as the resin quantity, on the mechanical parameters, are discussed.

Keywords

composite, reinforcement, anisotropy, tensile curve, mechanical properties, structure, degradation, cracking, delamination.

1. Introduction

Reinforced plastic composites are a special type of material due to geometric features, properties and technology used in their manufacturing [14, 16]. Compared to the metallic materials such as steels and alloys, they have a layered structure with a specific reinforcement configuration with respect to the matrix and volume contribution of components. Their type, arrangement and content directly decide on the mechanical properties of the composite, providing product that fits well to the specific industry needs [18]. Various types of glass fibres are used for their reinforcement. Their chemical composition mainly contains: SiO_2, Al_2O_3 and CaO [9, 13]. Basic mechanical parameters of these composites, such as the Young's modulus (E), ultimate tensile strength (R_m) and elongation are kept within the following limits: 51.7÷85.5 [GPa], 2.415÷4.890 [GPa] and 4.4÷5.7 [%], respectively. Plastic composites with a relatively wide range of mechanical parameters, e.g.: $E = 80.5÷43\,700$ MPa, $R_m = 64÷785$ MPa, $A_X = 0.02÷20$ % [13] can be obtained by a combination with the plastic matrix (polyester, epoxy, polyamide [19]). Taking into account applicability of the reinforced plastic composites one can indicate their suitability in motor transport [14], aviation and defence industries [14] and construction [1, 11]. In the case of first two industrial branches, a role of the plastic composites is mainly associated with lowering of the nominal mass of the transport vehicles. The military industry uses such materials to increase the ballistic resistance of the VIP and military vehicles [14]. In the construction industry, composites are used to produce reinforcing bars [1, 11] to increase the fatigue life of structures [1].

The scope of experimental works for the composite properties assessment includes tests involving a determination of the reinforcement type impact on mechanical parameters under quasi-static tension and dynamic loading conditions [12]. Also, intensive investigations are carried out to determine a role of percentage of the reinforcement content on the micro-hardness, yield point, ultimate tensile strength and elongation [10]. Moreover, tests are often conducted to determine changes of mechanical properties of composites in question using specimens that are cut from plates in different directions with respect to theirs symmetry axis [3, 7]. However, the results [3, 7] show the stress-strain relationship and changes in the strength, only. There are no any info on the Young's modulus, proportional and elastic limits as well as yield point. Some laboratories carry out shear tests on V-notched specimens mounted on a specially designed device (Iosipescu test) [8]. Characterization of the mechanical properties of composites often includes bending tests, results of which can be used to assess an effect of the reinforcement layer type on the strength parameters, deflection at maximum force and Young's modulus [4]. Also, such results are suitable in the composite's behaviour modelling during loading process at the three-point bending test, particularly in the elastic range [5].

Many efforts are focused on analysis of the resistance of composites subjected to impact enforced by different values of the kinetic en-

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ergy. An influence of the loading type on the stress-strain characteristics during the three-point bending test also belongs to the still hot subjects under consideration [6]. Nowadays, a damage degree of the composites with various types of reinforcement due to tensile and bending tests are usually analysed using SEM technique [2]. These studies are often supported by the use of digital image correlation (DIC) [17]. The results presentation of such tests includes the full-field strain distributions and changes in the Young's modulus and Poisson's ratio as a function of the principal components of strain that are dependent of specimen orientation taken from the plate in question. It gives an excellent basis for pointing out a potential places of the best or the weakest mechanical properties. With regard to the bench tests of the reinforced plastic composites one can indicate the firing tests that are applying for determination of the ballistic resistance. Also, both the matrix and reinforcement, that form a shield either against the projectile impact or explosive charge, are taken into account separately [15].

Tab. 1. Physical properties of the CD600 polymer-glass composite

Specimen No.	Composite mark	Number of reinforcing layers	Weight [kg]	Glass fibres content [%]	Resin content [%]	Thickness [mm]
2	CD600	3	3.34	53.6	46.4	2.30
3		6	4.3	67	33	3.20
5		10	7	68.6	31.4	4.90

The composite introduction into service is usually based on the product card providing data on: density, impact strength, yield point, Young's modulus, compressive and shear strength in two mutually perpendicular directions, thermal expansion and thermal conductivity coefficients [20]. In practice, composites are subjected not only to simple loading conditions, but also to the complex stress states reflecting rotation of the principal stress components with respect to the direction of the most favourable mechanical properties. As a consequence, the values of stress components occurring in the material may exceed the critical ones in some directions. It may lead to the earlier damage than that previously assumed, development of defects, and finally the item destruction. In order to eliminate such situations, the mechanical properties of the composite should be determined at least for three directions giving as a consequence, more complete knowledge regarding the stress-strain characteristics and mechanical properties of the material tested. In addition, microscopic observations of the fractured zone should be carried out in order to reflect a specific character of damage process of the reinforced plastic composites. Only the full set of results from investigations covering mechanical tests on material taken from several directions, SEM and macro photography enables rational inference on the composite behaviour under a specific loading. Therefore, the main aim of the paper is to assess mechanical parameters and structure variation due to tension of the polymer-glass composite using macroscopic and microscopic techniques.

2. Details of the testing technique for determination of the mechanical properties anisotropy

The CD600 composite was subjected to tests. It had 3, 6 or 10 reinforcing layers. The percentage content of glass fibres and resin was dependent on the number of layers and thickness, Tab.1. The changes of the physical-chemical properties of the material can be observed through colour, reflectivity and light transmittance., Tab. 2.

In order to reflect a possible anisotropy of the mechanical properties of composite, the specimens were cut out in three directions: 0°, 45° i 90° (Fig. 1). Subsequently, they were subjected to tension, in order to capture stress-strain characteristics (Figs. 2, 3). Having them, the following mechanical parameters were determined: Young's modulus, elastic limit, yield point, and ultimate tensile strength (Tab. 3). Variations of the mechanical parameters are presented in Fig. 4 as a function of: (a) number of layers of the reinforcing mat (Fig. 4), (b) direction from which the specimen was taken (Fig. 5), (c) percentage of glass fibres (Fig. 7) and resin (Fig. 8).

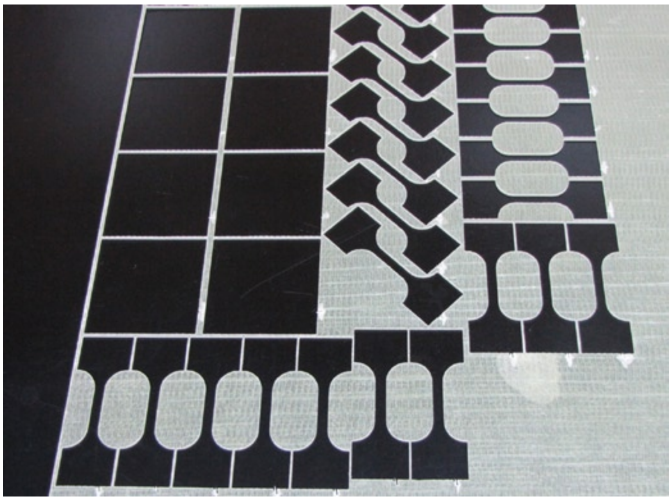


Fig. 1. Arrangement of flat specimens for tensile tests and square-shaped specimens for penetration tests in the CD600 polymer-glass composite plate

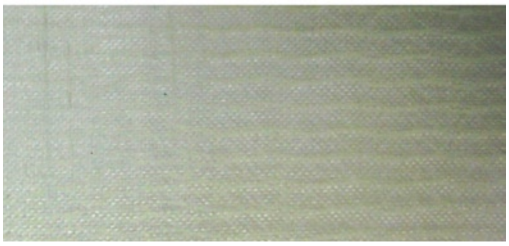
3. Mechanical properties and structure of the composite subjected to tension

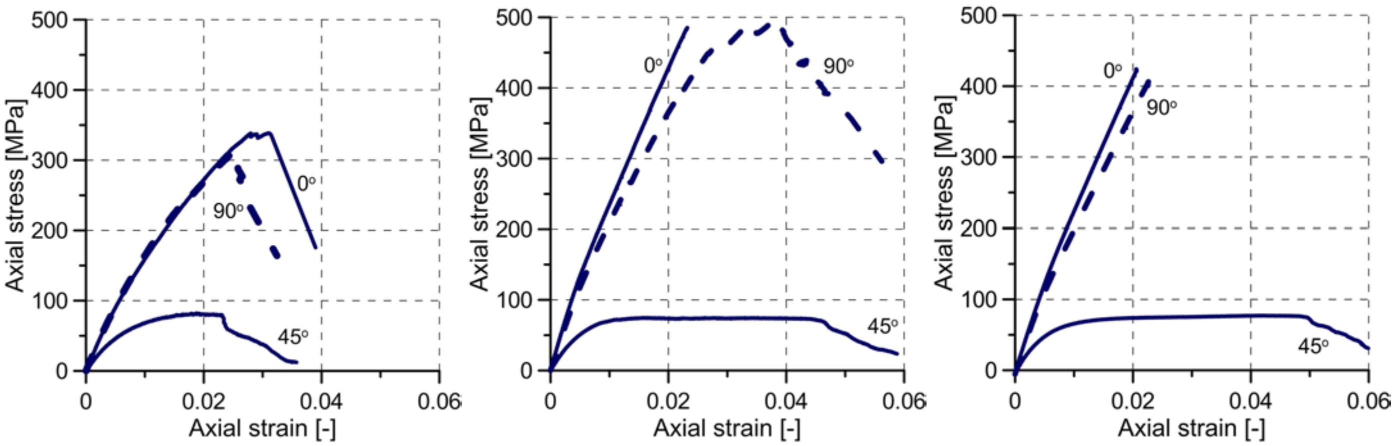
A mechanical behaviour of the composite under tensile conditions was dependent on the number of reinforcing layers, direction from which specimens were taken, and percentage contribution of components. It was manifested by differences in the shape of tensile characteristics and values of mechanical properties determined (Fig. 2). In the case of composite with three layers of reinforcement, each of the stress-strain characteristics represented the elastic-plastic behaviour with a section of instability (Fig. 2a), indicating certain ability of the material to transfer loading even after obtaining the ultimate tensile strength. A two-fold increase of the reinforcing layers number led to significant differences of the stress-strain relationships for the 0 and 90° directions, representing respectively, a quasi linear-elastic and elastic-plastic courses with a section of instability under almost the same tensile strength (Fig. 2b).

Composite with 10 layers of reinforcement (Fig. 2c) did not show any significant differences of the tensile characteristics in the case of 0 and 90° material orientations, giving simultaneously a lower tensile strength values than those achieved for the composite with 6 layers (Figs. 2b and 3a, c). In the case of composite tested in the 45° direction (apart from some differences in tensile curves showing elastic-plastic behaviour with the instability range for the 3 layers composite and elastic-plastic behaviour with the clear „plastic plateau" for the 6 and 10 layers composite) the variations of ultimate tensile strength were negligible small. It indicates that this parameter is not affected by the number of layers (Figs. 2, 3b, Tab. 3).

Comparison of the tensile characteristics of the composite for different content of reinforcing layers with regard to the material elastic-plastic features shows their vanishing with the increase of the reinforcing layers number in the case of specimen directions that were mutually perpendicular (0° and 90°) (Figs. 2, 3a, c). The tests show that the tensile curves for specimens of the 90° direction exhibit the best mechanical properties in the case of 6 reinforcing layers, Fig. 3c. On the other hand, the similarity of tensile curves for the 45° direction identifies no influence of the number of reinforcing layers, and

Table 2. A view of the outer layer of the CD600 composite depending on the number of reinforcing layers

Specimen No.	Composite mark	Photo of the composite	Unifilo M 861-450 mat, which is the reinforcement of the composite
2	CD600 (3 layers of reinforcement)		
3	CD600 (6 layers of reinforcement)		
5	CD600 (10 layers of reinforcement)		



(a) 3 layers *(b) 6 layers* *(c) 10 layers*

Fig. 2. Tensile characteristics of the CD600 composite with a different number of reinforcing layers taken from three directions: 0°, 45°, 90°

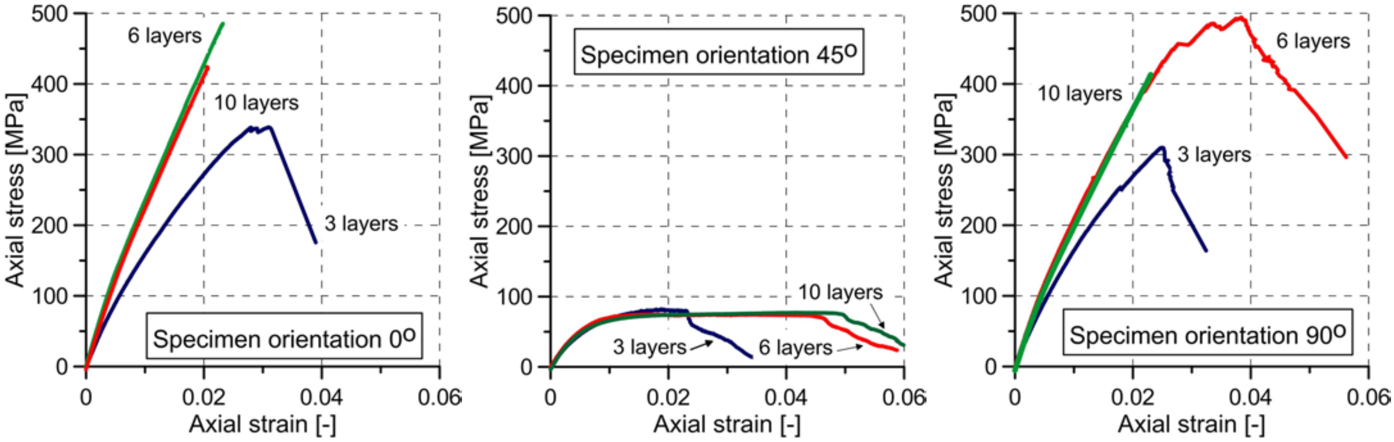
thus, the percentage content of the composite components in question, on the ultimate tensile strength (Fig. 3b). Analysis of the elongation variations exhibited its increase with an increase in the number of reinforcing layers.

An influence of the reinforcing layers number on the mechanical parameters was evaluated on the basis of the results shown in Fig. 4. Regardless of the orientation from which the specimen was cut, the Young's modulus increased with an increase of the reinforcing layers number. Variations of the elastic limit and yield point showed similar character, however, for the 90° direction, only. The dependence of tensile strength on the number of reinforcing layers exhibited a similar character for specimens of 6 reinforcing layers tested in 0 and 90° directions (Fig. 4d).

Comparison of mechanical parameters (Tab. 3) as function of specimen orientation enables identification of the so-called „saddle effect", expressed by the lowest values of the Young's modulus, elastic limit and yield point as well as ultimate tensile strength obtained for the 45° direction (Fig. 5b). Additionally, it is possible to indicate which of the mechanical parameters was the most dependent on the number of reinforcing layers. In the case of composite tested, it was the Young's modulus, which taken higher values as the reinforcement content increased for each specimen direction considered, Fig. 5a. Other mechanical parameters, such as: elastic limit (Fig. 5b), yield

Table 3. Mechanical parameters of the CD600 composite depending on the number of reinforcing layers and direction of material collection for tests

Number of reinforcing layers	Material collection orientation	Young's modulus [MPa]	Elastic limit [MPa]	Yield point [MPa]	Ultimate tensile strength [MPa]
3	0°	18 179	75	137	322
	45°	10 701	37	54	69
	90°	18 542	112	204	327
6	0°	25 034	140	245	480
	45°	12 719	41	60	75
	90°	22 953	132	231	431
10	0°	25 753	114	198	409
	45°	14 256	38	55	79
	90°	24 455	154	257	382



(a) (b) (c)

Fig. 3. Comparison of the tensile characteristics of the CD600 composite with different content of the reinforcing mat layers, determined for three orientations of specimens: 0° (a), 45° (b), 90° (c)

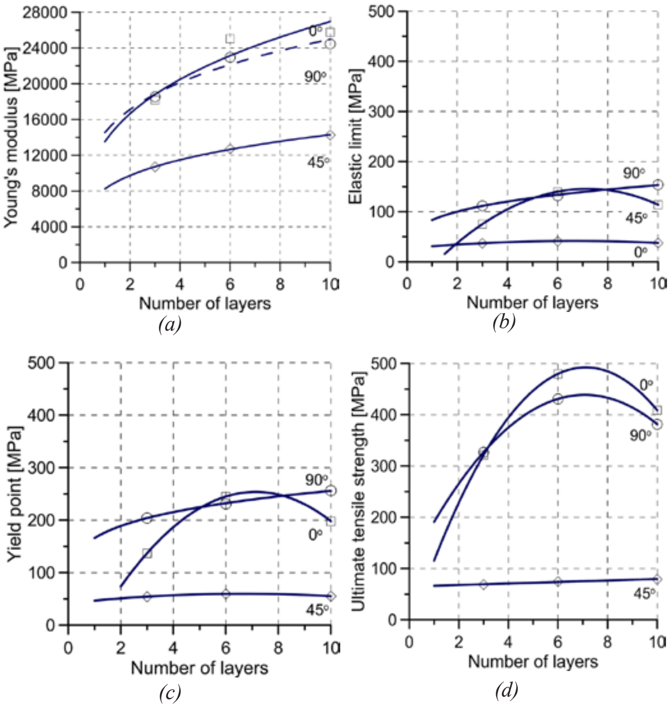


Fig. 4. Mechanical parameters of the CD600 composite depending on the number of layers of the reinforcing mat

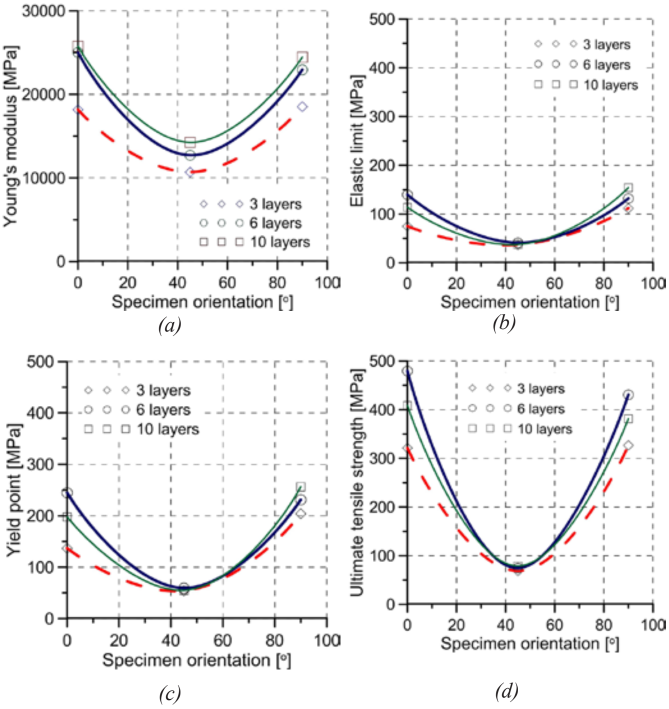


Fig. 5. Variation of the CD600 mechanical parameters, depending on the number of reinforcing layers as a function of the specimen orientation

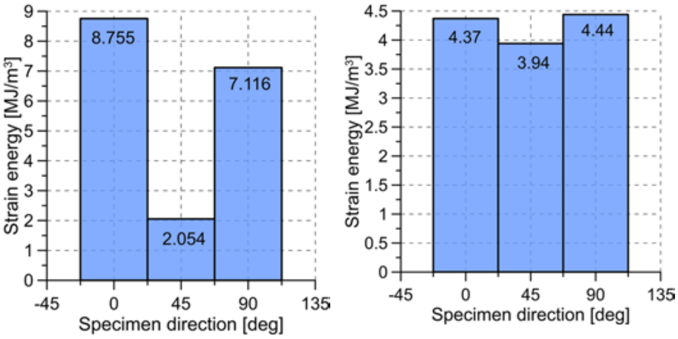


Fig. 6. Total strain energy from the tensile tests of the CD600 composite with a different number of reinforcing layers depending on the specimen orientation

point (Fig. 5c) and ultimate tensile strength (Fig. 5d) did not show such any marked increase in value. For the 45° direction they were constant, regardless of the number of layers of reinforcement.

The program carried out also made it possible to assess a strain energy variation depending on the material orientation and the number of reinforcing layers (Fig. 6).

Based on these results, some important conclusions can be formulated regarding the material's ability to absorb energy in the individual directions. In the case of the 10 layers composite, that showed the mechanical properties anisotropy, practically, an identical values of the strain energy were obtained independently on the orientation from which the material was taken (Fig. 6b). However, such effect was not observed for the three-layer composite, Fig. 6a.

One of the main objectives of the research was to obtain results that would give some guidelines of technological importance. For this reason, an influence of the composite components content on its me-

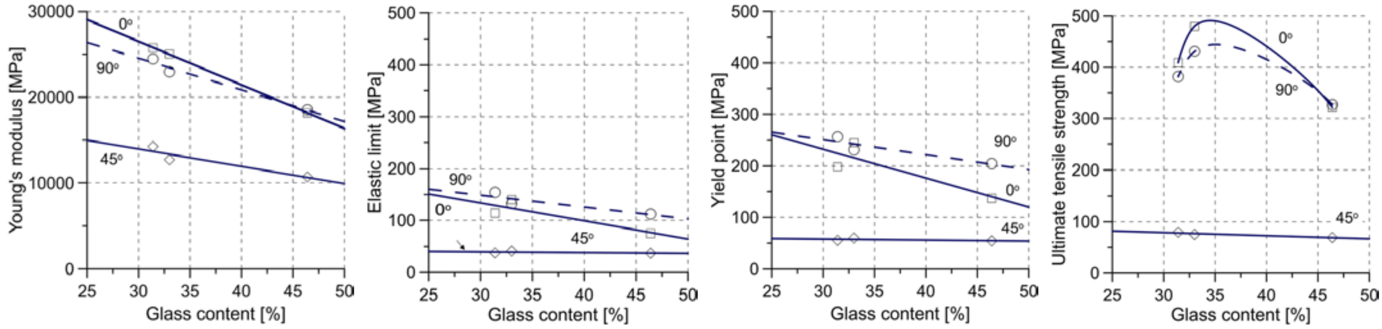


Fig. 7. Mechanical parameters of the CD600 composite depending on the glass fibres content for the three orientations of specimens

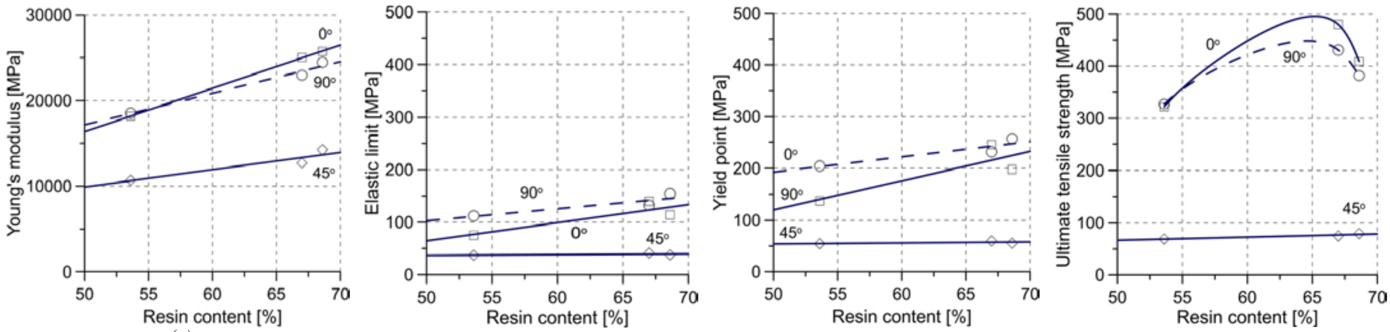


Fig. 8. Mechanical parameters of the CD600 composite depending on the resin content

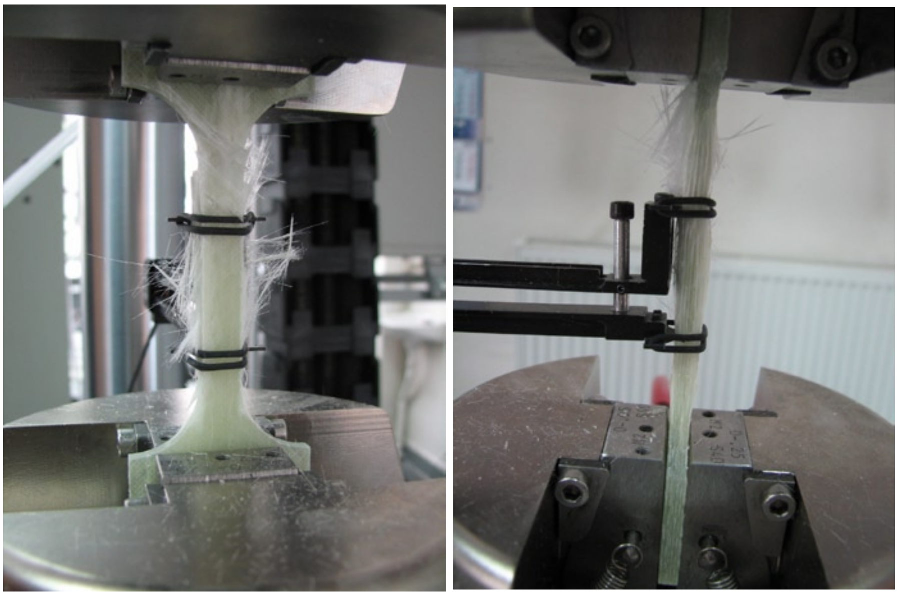


Fig. 9. Specimen No. 5 (10 layers of reinforcement) from the CD600 composite in the final stage of tensile test

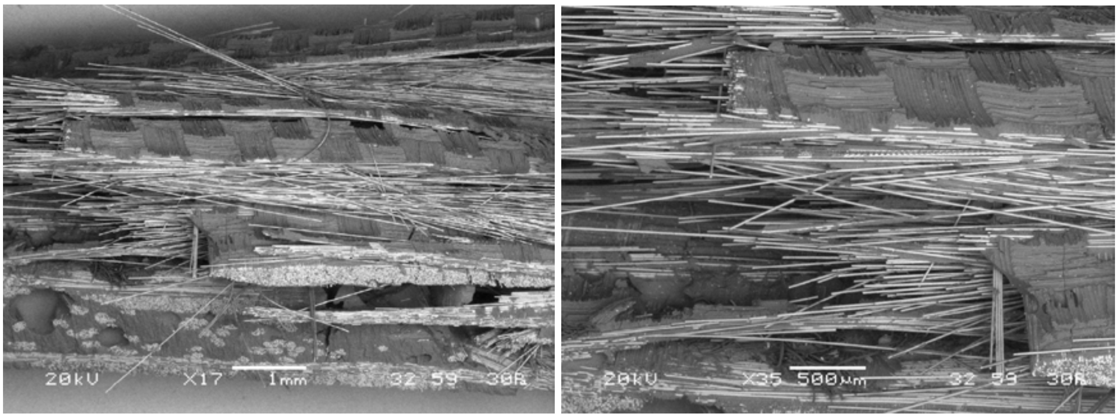
chanical parameters was analysed. The nature of the Young's modulus, elastic limit, yield point and ultimate tensile strength changes as a function of glass fibres content is given in Fig.7. The first three mechanical parameters mentioned above, exhibited a decrease with an increase of the fibre content percentage in all directions taken into account, i.e. 0°, 45° and 90° (Figs. 7a, b, c). Solely in the case of tensile strength the character of changes was different. Namely, in directions mutually perpendicular - 0° and 90°, an increase of strength was observed at the beginning, and subsequently, its decrease. It has to be emphasised, that the turning point of such behaviour was the fibre content of 35% (Fig. 7d). Interestingly, the ultimate tensile strength had a slightly downward tendency with the increase of the percentage content of reinforcement in the case of 45° direction (Fig. 7d).

The resin content had a completely different impact on the mechanical parameters of the composite tested (Fig. 8). The increase of resin

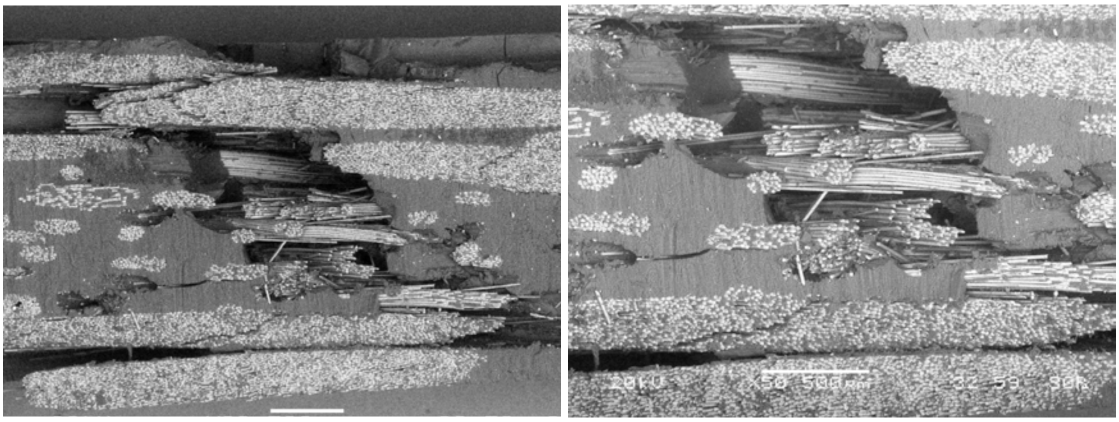
Fig. 10. Specimens of the composite (10 layers of reinforcement) after tensile test, taken from 45º, 0º and 90º direction, respectively

content resulted mostly on the mechanical parameters increase. Only for the 45° direction the composite did not react on changes of the resin content, practically. Similarly to analysis of the influence of the reinforcing phase content on the basic mechanical parameters, also the resin content had a different effect on the material strength in comparison to the other tensile test parameters considered here. As shown in Fig. 8d, with the resin content increase, the tensile strength initially increased (to a resin content of about 65%), and then clearly decreased. Such behaviour was obtained for the specimens cut in the 0° and 90° directions. The result achieved gives a knowledge necessary to indicate the most optimal proportion of glass fibre and resin content namely, it was 0.53 for the test conducted in this experimental program.

The knowledge of the composite content makes material damage monitoring easier on each individual stages of mechanical loading (Fig. 9). It is possible thanks to the assessments of reinforcement behaviour captured for several directions in order to reflect the specifics of damage process of the material tested.



a)



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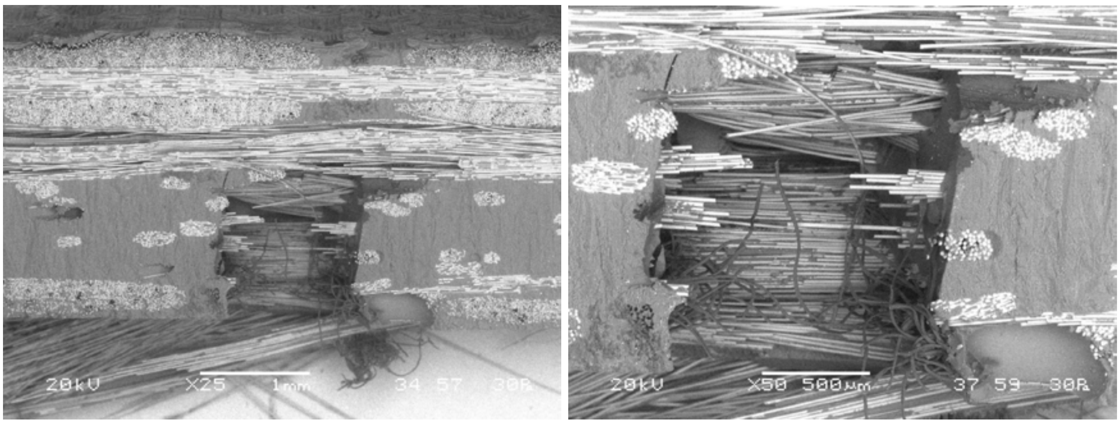


c)

Fig. 11. Damage zones of the CD600 composite (3 layers of reinforcement) obtained by SEM technique after tensile test: a) 0° direction, b) 45° direction, c) 90° direction

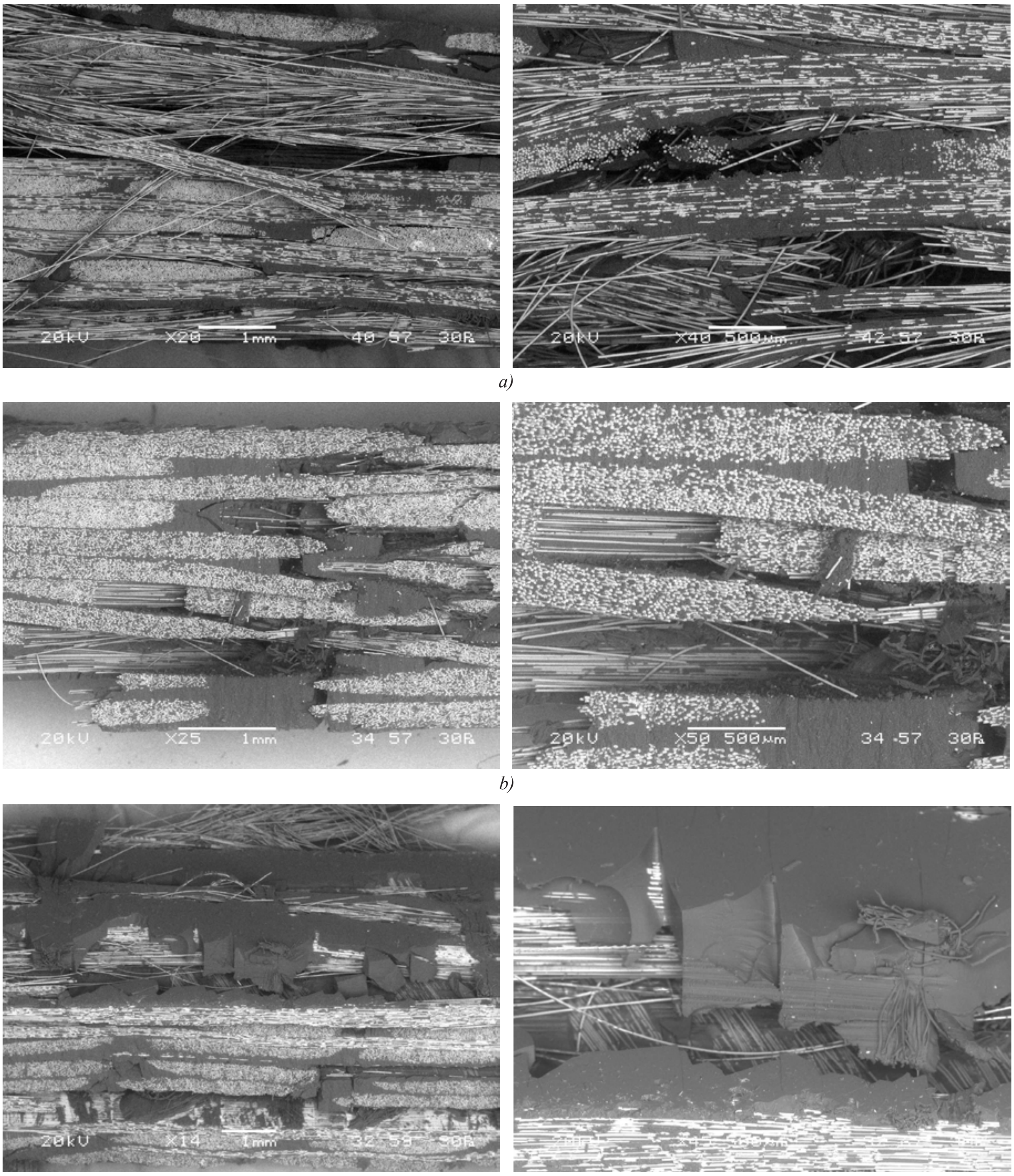
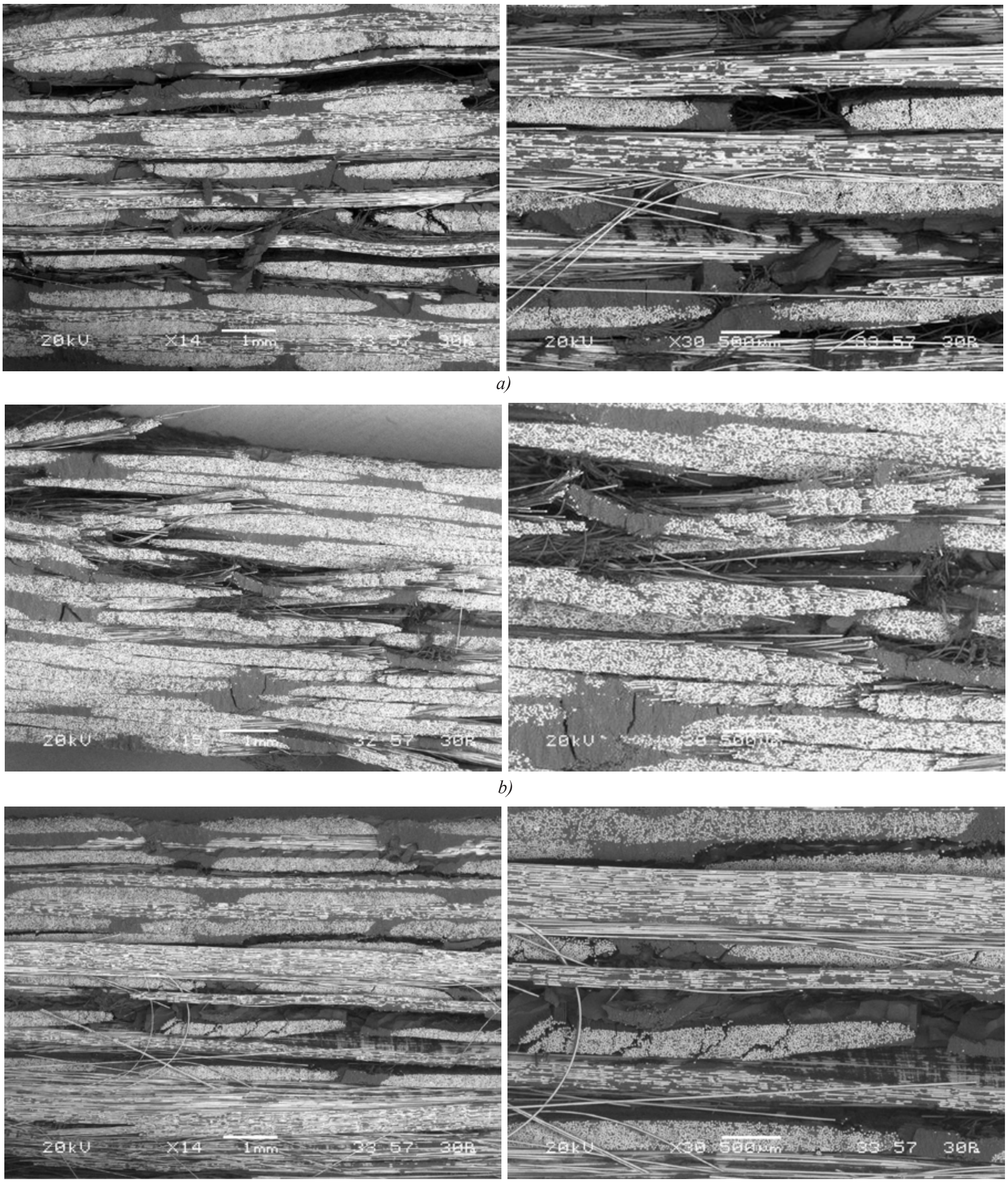


Fig. 12. Damage zones of the CD600 composite (6 layers of reinforcement) obtained by SEM technique after tensile test: a) 0° direction, b) 45° direction, c) 90° direction

The gauge lengths of the composite specimens after the tensile test were used to collect a necessary data characterising damage zones (Fig. 10). In the case of specimen cut along the 0° direction, the degradation process took place along the main specimen axis. Specimens of 45° direction showed damage in the plane of maximum tangential stress. In the last group of specimens (90°) the damage developed in many directions, causing delamination of the material tested.

Damage observations in the matrix, reinforcement and their connecting zone using SEM technique showed characteristic features (Figs. 11-13). Cleavage fracture of the glass fibres and matrix with the fracture front displacement due to the local weakening of the reinforcement was a characteristic type of material damage process for the 0° direction in the case of a composite containing 3 layers of reinforcement (Fig. 11a). For the composite taken from the 45° direction, the diagonal fracture front and its delamination were the dominant forms of damage (Fig. 11b). Cleavage fracture of the glass fibres and matrix was the basic damage mechanism for the composite specimens taken from the 90° direction (Fig. 11c). Damage developing in 0° direction of the composite containing twice the number of layers of reinforcement occurred due to significant contribution of cracking glass fibres, that caused a local loss of bearing capacity (Fig. 12a). The structure of the material cut along the 45° direction degradated due to the matrix cleavage fracture, characterized by fracture front displacement and slight delamination, Fig. 12b. In the case of material taken from the 90° direction, the process of delamination dominated in structural fracture (Fig. 12c). Degradation of the composite having 10 layers of reinforcement for the 0° direction was characterized by the matrix cracking and delamination (Fig. 13a). Only delamination was involved in fracture process of the material taken from the 45° direction. Additionally, it exhibited displacement due to the earlier



a) b) c)

Fig. 13. Damage zones of the CD600 composite (10 layers of reinforcement) obtained by SEM technique after tensile test: a) 0° direction, b) 45° direction, c) 90° direction

durability loss of the matrix-reinforcement connection (Fig. 13b). The delamination was also responsible for a degradation of the composite structure in the case of material taken from the 90° direction, (Fig. 13c).

4. Summary

The polymer-glass composite CDP600 showed different courses of tensile characteristics depending on the specimens orientation in the plate tested. As a consequence, the basic mechanical parameters: Young's modulus, elastic limit, yield point and ultimate tensile strength varied significantly depending on the direction.

Mechanical parameters of the polymer-glass composite considered in the 45° direction were the least dependent on the number of reinforcing layers and percentage of components constituting the material.

Differences of the total strain energy associated with the tensile curve of the composite tested in 0, 45 and 90° directions were reduced with the increase of the reinforcing layers number, taking almost identical values as that for the 10 reinforcing layers composite achieved.

Increasing the number of reinforcing layers led to changes of the composite degradation mechanisms. For the smaller number of layers, the fracture took the nature of a cleavage fracture, whereas for the larger a delamination mainly occurred.

Introduction of composites into service and the subsequent assessment of their technical condition should be carried out using the results of tests identifying an anisotropy of mechanical properties and features of structure degradation.

References

1. Alsayed S, Al-Salloum Y, Almusallam T, El-Gamal S, Aqel M. Performance of glass fiber reinforced polymer bars under elevated temperature. Composites: Part B 2012; 43: 2265-2271, https://doi.org/10.1016/j.compositesb.2012.01.034.
2. Arasau P M, Karthikayan A, Venkatachalam R. Mechanical and thermal behavior of hybrid glas/jute fiber reinforced composities with epoxy/polyester resin. Polimery 2019, 64(7-8): 504-508, https://doi.org/10.14314/polimery. 2019.7.6.
3. Bakir B, Hashem H. Effect of Fiber Orientation for Fiber Glass Reinforced Composite Material on Mechanical Properties. International Journal of Mining, Metallurgy & Mechanical Engineering 2013; 1(5): 341-345.
4. Bienias B, Michalski W, Wagner L. Mechanical strength evaluation of poly(methyl methacrylate) reinforced with long glass, carbon and aramid fibers. Polimery 2019; 64(6): 417-421, https://doi.org/10.14314/polimery.2019.6.4.
5. Buchacz A, Baier A, Herbuś K, Ociepka P, Grabowski Ł, Sobek M. Compression studies of multi-layered composite materials for the purpose of verifying composite panels model used in the renovation process of the freight wagon's hull. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (1): 137–146, http://dx.doi.org/10.17531/ein.2018.1.18.
6. Komorek A, Przybyłek P. Examination of the influence of cross-impact load on bend strength properties of composite materials, used in aviation. Eksploatacja i Niezawodnosc - Maintenance and Reliability 2012; 14 (4): 265-269.
7. Hegde A, Darshan R S, Mulla F, Shoeb M, Rajanish M. Tensile properties of unidirectional glass/epoxy composites at different orientations of fibres. Int. Journal of Engineering Research and Applications 2015; 5(3): 150-153.
8. Herakovich C.T. Mechanics of composites: A historical review. Mechanics Research Communications 2012; 41: 1-20, https://doi.org/10.1016/j.mechrescom.2012.01.006.
9. Hulsenberg D, Fehling F, Leutbecher T. Damage tolerant, translucent oxide fiber/glass matrix composites. Composites: Part B 2008; 39: 362-373, https://doi.org/10.1016/j.compositesb.2007.01.002.
10. Jagannatha TD, Harish G. Mechanical properties of carbon/glass fiber reinforced epoxy hybrid polymer composites. Int. J. Mech. Eng. & Rob. Res. 2015; 4(2): 131-137.
11. McDaniel G, Knight C. Fiber Reinforced Polymer (FRP) Composites 2014. Design Training Expo, Composites and Advanced Materials Expo October 13-16, 2014, Orange County Convention Center Orlando, FL.
12. Ramesh M, Palanikumar K, Reddy K H. Mechanical property evaluation of sisal-jute-glass fiber reinforced polyester composites. Composites: Part B 2013; 48: 1-9, https://doi.org/10.1016/j.compositesb.2012.12.004.
13. Sathishkumar TP, Satheeshkumar S, Naveen J. Glass fiber-reinforced polymer composites - a review. Journal of Reinforced Plastics and Composites 2014; 33(13): 1258-1275, https://doi.org/10.1177/0731684414530790.
14. Stickel JM, Nagara JM. Glass Fiber-Reinforced Composites: From Formulation to Application. International Journal of Applied Glass Science 2012; 3(2): 122-136, https://doi.org/10.1111/j.2041-1294.2012.00090.x.
15. Szudrowicz M. Layered composite increasing the resistance of patrol and intervention vehicles to the impact of improvised explosive devices (IED) from below. Eksploatacja i Niezawodnosc - Maintenance and Reliability 2018; 20(1): 9-15, https://doi.org/10.17531/ein.2018.1.2.
16. Verpoest I., Composites Materials Research Challenges, Composites Materials Research Challenges", Katholieke Universiteit Leuven Belgium, 2013, 27 pages.
17. Vogel K., Heinrich M., Ulbricht J., Elsner H., Feige H.J., Vogel J., Kroll L. Mechanical characterization of glass fiber-reinforced composites, XIIIth Youth Symposium on Experimental Solid Mechanics, June 29th - July 2nd, Decin, Czech Republic, 2014, 137.
18. Advanced Composite Materials, Chapter 7, 2.
19. GTC-4-011-1, Guide to composites, Gurit, 73 pages.
20. Physical Properties of GFRC Stone Wear Information, 9 pages.