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Scientific paper

BALISTIČKA ČVRSTOĆA TKANINA NAMENJENIH ZA LIČNU ZAŠTITU

BALLISTIC STRENGTH OF WOVEN FABRICS FOR PERSONAL PROTECTION

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Izvod

Cilj istraživanja je bio da se opredeli balistička čvrstoća četiri različita vlakna-smola kompozita namenjenih za ličnu balističku zaštitu.. Istraživanje je vršeno na kompozite izradjenih od tkanina na bazi staklenih, najlonskih, aramidnih i HPPE (visoko-prformansni polietilen) vlakana. U svim slučajevima kao matrica je koriščena fenol-formaldehidna smola modifikovana polivinilbutiralom. Za ovo istraživanje uzeta je površinska masa za kompozite u opsegu 2-9 kg/m^2, opseg koji ima smisla za ličnu balističku zaštitu, a sadržaj smole je bio u opsegu 20-50 %. Balistička test je pokazao da najbolje rezultate pokazuju kompoziti na bazi HPPE tkanine, zatim slede aramidni kompoziti a iza njih oni na bazi balističkog najlona. Najlošije rezultate su pokazali kompoziti na bazi staklene tkanine.Svi kompoziti sa niskim sadržajem smole (~20 %) pokazali su mnogo bolje rezultate nego oni sa velikim sadržajem smole (~50 %). Dijagram balističke čvrstoće V_{50} u zavisnosti od površinske mase pokazao je linearno povećanje V_{50} sa povećanjem površinske mase kompozita. Balistička čvrstoća kompozita na bazi tkanina veoma zavisi od odnosa vlakna /smola i povećava se sa povećanjem sadržaja vlakana.

Ključne riječi:*Balistički kompoziti, aramid, e-staklo.*

Abstract

The purpose of the research was to make evaluation of the ballistic strength of four different fiber/resin composites intended to be used in manufacturing of ballistic items for personal protection. Research has been performed on glass, ballistic nylon, aramid and HPPE (High Performance Polyethylene) plain woven fabrics based composites. As a matrix system, in all cases, polyvinylbutyral modified phenolic resin was used. For the investigation, areal weight range 2-9 kg/m^2, applicable range for this items, and resin content range was 20 -50. %. Ballistic test of the composites has shown that the best results exhibit HPPE based composites: aramid based composites have been the second best, followed by the polyamide based composites. The worst results have been shown by the glass based composites. All the composites with lower resin content (~20 %) have performed much better than their *counterparts with higher resin content (~50 %). The plot of the ballistic strength, V_{50}, versus areal weight has shown a linear increase of V_{50} with the increase of areal weight within the investigated range. The ballistic strength of the woven fabric composites is highly dependent on the fiber/resin ratio and increases with the increase of fiber content.*

Key words: *Ballistic composites; aramid; E-glass*

1. INTRODUCTION

The purpose of the research was to make evaluation of the ballistic strength of four different fiber/resin composites intended to be used in manufacturing of ballistic items for personal protection. Fabrics are extremely important part of modern armors. Also extremely important are composite laminates made of fabric sheets stiffened with resin. Fibrous armor has importance for several reasons. Since man utilizes clothing in normal life, protective devices that can be incorporated into such clothing provide the most comfortable, compatible and inconspicuous method of providing such protection. The second reason fibers are important is that they provide the greatest strength and modulus properties that can be obtained from a given material. In the case of polymers, this is due, mainly, to the drawing operation which orients the molecules along the fiber axis increasing strength and stiffness and providing also a natural crack arresting mechanism [1].

Fiberglass is one of the best known, and in a way, the most unusual laminate prepared from glass fabric and used extensively in the construction industry, boats, etc. It is well known in ballistic application because of the research conducted during World War II, which resulted in a fragmentation protective vest. It is an unusual laminate in that fiberglass, a fabric with poor ballistic resistance unlaminated, when combined with synthetic resin, another material with poor impact and ballistic resistance, results in a material with excellent ballistic resistance either alone or as a backup for a harder material. The resin, although present in a small percentage (~20%) mitigates the defects which can easily be introduced into glass and lower the strength. Despite the existence of glass fabrics laminates (composites) before the World War II, the work of Carothers [2] at DuPont in the early 1930s was necessary to make fabric armor reality. Carothers' research on macromolecules, recognizing the need for a molecular weight of at least 12000, a molecular length of 100 nm, and preferably a crystallizable morphology, led to nylon fibers which could be prepared uniformly and cheaply with high strength. The second laminate of longtime use by the military is that prepared from nylon fabric in combination with a phenolic resin. At that time, the main advantage of nylon laminates was in their excellent ballistic resistance and lower weight, compared to glass laminates.

The second breakthrough occurred in the early 1960s when DuPont scientists were experimenting with stiff polymers usually considered intractable. They came up with a new aramid fiber three times as strong as nylon and with a far higher modulus and heat resistance [3, 4]. Even though it had a higher modulus, the resulting fibers were so fine that the resulting fabric possesses flexibility and drape. The military seized upon this new material known as Kevlar 29 and produced vests with lighter weight and higher protection values that would have been imagined before. Kevlar 29 is one of the most amazing man-made fibers. This para-aramid fiber is characterized by its high tenacity and modulus of elasticity, low density as well as high energy absorption [5]. Aramid fibers have been dominant fibers in ballistic application until 1979 when the Dutch company DSM invented and patented super strong polyethylene fibers as well as the gel spinning process to produce it.

The basic theory about how to produce a super strong fiber from a polymer such as polyethylene is easy to understand. Polyethylene with an ultra high molecular weight (UHMW-PE) is used as the starting material. In normal polyethylene the molecules are not oriented and are easily torn apart. In the gel spinning process the molecules are dissolved in a solvent and spun through a spinneret. In the solution, the molecules that form clusters in the solid state, become disentangled and remain in that state after the solution is cooled to give filaments. As the fiber is drawn, a very high level of molecular orientation is attained resulting in a fiber with a very high tenacity and modulus [6, 7]. Called Dyneema, this high performance polyethylene (HPPE) fiber is now available in different grades. It is characterized by a parallel orientation greater than 95 % and a high level of crystallinity (up to 85 %). This gives HPPE fiber its unique properties. The density is slightly less than one (0.97 g/cm^3), so the fiber floats on water. The tenacity is highest in the world and can be up to 15 times that of good quality steel [8]. The modulus is very high and is second only to that of a special carbon fibers grade. Elongation at brake is as low for HPPE fibers as for other high performance fibers, but due to the high tenacity the energy to break is high.

2. EXPERIMENTAL

2.1 Materials

The resin matrix, for impregnation of the woven fabrics, was resol type phenolic modified with polyvinylbutyral. The properties of the reinforcing fabrics are presented in Table 1.

Table1. Properties of the applied fabrics

Property	Unit	Glass fabric	Nylon 6.6 fabric	Aramid fabric	HPPE fabric
Designation		7628	FG2006/E	T713	5006
Weave		1x1	1x1	1x1	1x1
Areal weight	g/m^2	203±5	265±8	280±7	295±8
Thickness	mm	0.19	0.40	0.43	0.28
Yarn warp weft		 EC9 68tex EC9 68tex	 120tex 120tex	 1260dtex 1260dtex	 SK76 1760 SK76 1760
Tread count warp weft		 12.5 16.5	 15.0 15.0	 11.0 10.5	 8.0 8.0
Tensile strength warp weft	N/5cm	 1700 2100	 4200 4200	 9500 10000	 19300 19300
Finish		Universal, compatible with phenolic resins	Universal, compatible with phenolic resins	No finish	No finish

The prepreg material of all four fabrics was prepared on a semi-industrial, vertical impregnating machine. Two composite sets were manufactured, one with resin content of approx. 20 %, and the other – 50 %. The volatiles content in both sets was kept less than 1.5 %, and all the prepreg materials were manufactured with medium resin flow.

2.1 Molding

The laminates were constructed by laying up a multiple number of prepreg plies, in accordance with the targeted areal weight, and cured at 160 ^oC, except for the HPPE laminates which were cured at 130 ^oC. The applied pressure in all cases was 6 MPa. The prepared composites were with areal weight of 2, 3, 4, 5, 6, 7, 8, and 9 kg/m^2 because this is the weight range that makes sense for personal ballistic protection. The lower areal weight will not give appropriate protection while the higher than 9 kg/m^2 areal weight will be too heavy and tiring for the wearer of the ballistic protection making him/her uncomfortable and less mobile. The resin content range 20-50 vol. % is the ultimate which could be achieved with the semi-industrial production facilities available at “Eurokompozit” AD, Prilep, Macedonia, where all the samples were prepared.

2.3 Ballistic Test

Ballistic properties of composites were assessed by measuring their ballistic strength i.e. V_{50} ballistic limit. V_{50} ballistic limit test is a statistical test originally developed by the U.S. military to evaluate hard armor [9]. V_{50} test experimentally identifies the velocity at which a bullet has a 50 percent chance of penetrating the test object. Fundamental to the concept of ballistic limit is a relationship between the probability of penetration of the armor and the striking velocity of the projectile. The projectile-armor relationship satisfies the mathematical conditions of a probability distribution, i.e. for low velocities the probability approaches zero; for high velocities, the probability approaches one; and between these extremes of velocity the probability increases with the increase of velocity. When the general model describes the physical behavior, probability of penetration can be treated as a probability distribution and is usually described as a Gaussian or normal distribution. The probability of penetration is illustrated in Fig.1.

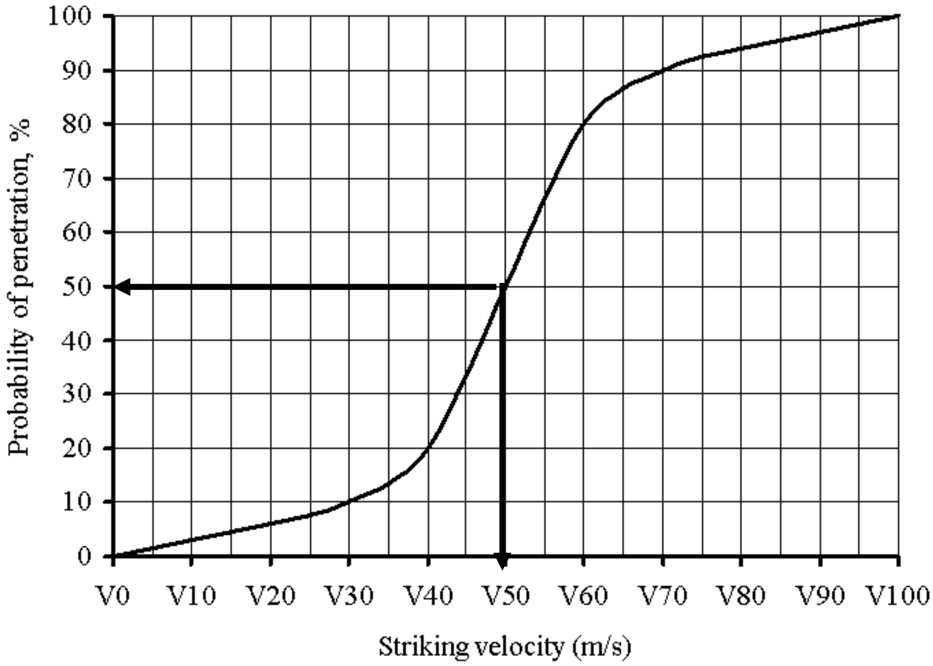

Fig.1. Probability of penetration vs. striking velocity

The normal Gaussian probability distribution curve has been found to give reasonably good representation of the probability of penetration in many cases. The ballistic test was performed by firing ϕ5.56 mm fragment simulating projectiles on to the composite panels. All test panels (400 mm x 400 mm) prior to testing were conditioned at a temperature of 20±20 ^{o}C and relative humidity of 65±5 %. At least 14 projectiles were fired at the test specimens and their velocities were measured. A projectile which passes through the panel or causes material to be thrown off the back of the panel was considered a complete penetration. All other impacts were defined as being partial penetrations. The V_{50} ballistic limit velocity for a panel is defined as that velocity for which the probability of penetration of the projectile is exactly 50%. After a number of projectiles have been fired the V_{50} is calculated as the mean of the velocities recorded for the fair impacts consisting of the seven highest velocities for partial penetration and the seven lowest velocities for complete penetration providing that all fourteen fall within a bracket of 60 m/s.

3. RESULTS AND DISCUSSION

A typical (sample) ballistic data processing sheet is given in Table 2. So that the test results could be valid the difference between mean values (dVa) of the partial penetrations (Vpa) and full penetration (Vfa) must not exceed 25 m/s which is in accordance to NATO standard STANAG 2920 which was implemented in ballistic tests. By Vp and Vf are designated single partial and single full penetrations respectively.

Table 2. A sample ballistic data processing sheet

Areal weight, kg/m^2	Velocity, m/s	Single shot velocity, m/s							Va, m/s	dVa, m/s	V_{50}, m/s
		1	2	3	4	5	6	7			
2	Vp	187.7	182.9	180.3	188.7	176.8	173.1	171.4	Vzsr= 180.1	16.6	188.4
	Vf	200.4	201.8	201.3	189.1	191.3	199.2	193.9	Vpsr= 196.7		
3	Vp	223.5	219.1	217.6	226.6	220.8	216.4	209.0	Vzsr= 219.0	13.4	225.7
	Vf	238.4	241.1	231.9	235.7	224.2	229.6	225.8	Vpsr= 232.4		
4	Vp	238.1	240.6	228.1	232.6	227.1	245.5	225.5	Vzsr = 233.9	15.4	241.6
	Vf	245.5	248.3	254.9	258.1	242.1	242.6	253.7	Vpsr = 249.3		
5	Vp	281.3	272.8	271.2	283.1	276.9	275.5	270.0	Vzsr = 275.8	10.2	280.9
	Vf	288.3	288.0	290.4	279.0	291.1	285.3	279.8	Vpsr = 286.0		
6	Vp	287.6	293.2	284.6	289.5	293.2	292.8	295.6	Vzsr = 290.9	13.8	297.8
	Vf	311.2	306.8	301.9	298.6	308.3	305.2	301.1	Vpsr = 304.7		
7	Vp	320.6	318.7	328.1	329.6	329.8	319.9	333.7	Vzsr = 325.8	17.5	334.6
	Vf	339.2	347.6	342.5	348.4	337.2	338.1	350.2	Vpsr = 343.3		
8	Vp	365.7	359.5	368.4	357.9	367.1	362.5	356.3	Vzsr = 362.5	15.4	370.2
	Vf	385.2	374.6	372.8	384.6	373.2	373.8	380.8	Vpsr = 377.9		
9	Vp	388.2	390.7	388.4	392.5	392.9	389.8	394.6	Vzsr = 391.0	9.2	395.6
	Vf	405.7	406.2	398.6	395.2	398.6	404.4	392.7	Vpsr = 400.2		

All ballistic test results are given in Fig.2. The difference in ballistic properties between various types of composites is more than obvious.

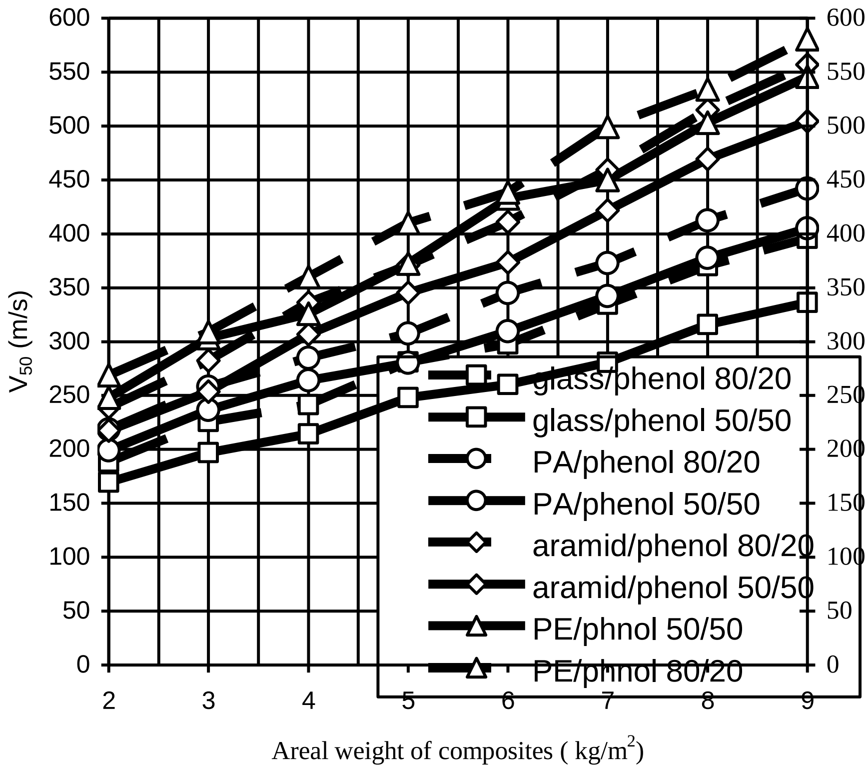

Fig.2.Ballistic strength vs. areal weight

Having in mind that all composites are processed under the same conditions, with the only exception that the molding of HPPE composites occurred at 130 °C, and that the same matrix is used in all composites, it is obvious that the difference in ballistic properties results from the different fiber i.e. fabrics properties. This means that the fibers have dominant role in determining the ballistic properties of the composites. The best ballistic results have been shown by the HPPE based composites and the worst – by the glass based composites. Aramid composites have performed slightly poorer than the HPPE composites but much better than the nylon based composites which on the other hand are superior to glass composites. Significant is that the slope of all curves is very similar. All the composites with resin content of 20 % have performed much better than their counterparts with resin content of 50 %. This leads to a conclusion that the ballistic properties of the composites, besides the fibers type, also very much depend on the fiber/matrix ratio, where a simple rule can be applied: the bigger the fiber content the better ballistic strength.

Which fiber property can affect more the ballistic strength of the composites is hardly to say. Cuniff et al. [10, 11] have taken a microscopic picture of the cross-section at the penetration point of the bullet into the composite and studied it very carefully. They have found out that the bullet tip causes tensile loading of the fiber, Fig.3.

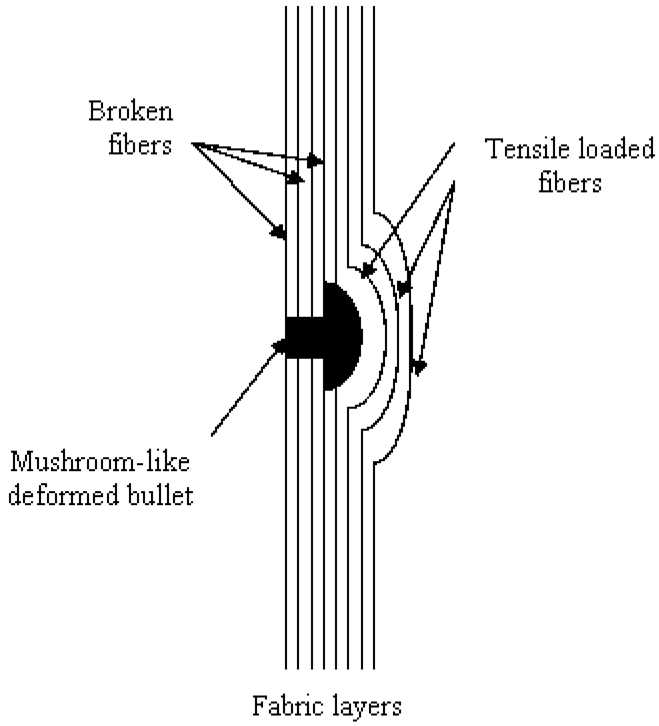

Fig.3. Cross-section of the composite at the bullet penetration point

The first few layers facing the bullet absorb maximum bullet energy in deforming and slowing it down. As a result, the fiber breakage occurs and the first few layers of the fabric are perforated. As the bullet penetrates further it deforms in a mushroom-like shape, tensile loads the fibers and loses much of its kinetic energy. The higher tensile strength of the fibers means higher resistance to the penetrating bullet and higher ballistic strength of the composites. In Table 3 the tensile strength values of the applied fibers are given.

Table 3. Mechanical properties of the applied fibers

Property	***Unit***	***E glass***	***PA***	***Aramid***	***HPPE***
Tensile strength	GPa	3.5	0.9	3.3	3.2
Modulus	GPa	72	6	75	95
Specific weight	g/cm^3	2.65	1.14	1.44	0.97
Elongation	%	4.8	20	3.6	3.7

As it can be seen, the ballistic strength of all organic fibers based composites matches the tensile strength of the applied fibers respectively.The only exception of this rule is the glass fiber composite, which although has higher tensile strength it has shown poorer ballistic resistance. In this respect Laible [12] concludes that the relationship between the mechanical properties of a yarn and the ballistic resistance of plied fabric prepared from such yarn has never been established. That means, solely, only on the tensile strength of the fibers one cannot predict the overall ballistic resistance of the composites. Another factor which influences ballistic strength is the sonic velocity of the fibers. The sonic velocity is the velocity of sound propagation into the fibers, or, in other words, that is the velocity of propagation of the shock or strain wave which is introduced into the fiber when it is hit by the projectile. The strain wave velocity is given by the following equation:

$$\nu = \sqrt{\frac{1}{\mu}\frac{\partial\sigma}{\partial\varepsilon}} = \sqrt{\frac{E}{\rho}} \qquad (1)$$

Where:

ν - sonic velocity of the fibers

μ - tex count

σ - fiber strength

ε - fiber elongation

E - modulus of elasticity

ρ - material density

When a projectile hits a woven fabric, a shock or strain wave is introduced which spreads through the yarns. The primary impacted yarns interact with other yarns by means of couplings at the cross-over points of the fabric. The strain wave can thus spread over a large number of yarns. The positive effect of this mechanism is that the energy will be absorbed over a relatively large area. The velocity of the strain wave and the energy dissipation is directly related to the modulus of the fibers.

In Table 4, the sonic velocity values of the applied fibers are given [13].

Table 4. Sonic velocities of the applied fibers

	E-glass	Polyamide	Aramid	HPPE
Sonic velocity (m/s)	5280	2200	8200	10000

As for the organic fibers based composites, there is a complete match between the ballistic strength and the respective sonic velocities of the fibers they are based on. The highest sonic velocity has HPPE fiber, followed by the aramid and polyamide fibers, and in this respect changes the ballistic strength of the composites. Here again, although glass fibers have higher sonic velocity, their composites show lower ballistic strength. The reason for that lies in the very different structure of the fibers. All applied organic fibers are characterized with parallel orientation of the molecules along the fiber axis (especially highly oriented are aramid and HPPE fibers, with orientation greater than 95%) which makes them highly anisotropic; all applied organic fibers are subjected to fibrillation-longitudinal splitting of the fiber under impact. The originally very fine fibers (12 μm) are subdivided by a factor of 10 or more by impact [14, 15]. The longitudinal fracture, somewhat typical of all fibers, becomes much more pronounced with the highly aligned molecules and certainly acts as an kinetic energy absorbent and efficient crack arrestor for any failure starting to occur transverse to the fiber. All applied organic fibers are flexible which is in marked contrast to the properties of glass fibers, which are brittle, isotropic and do not fibrillate under impact. All this disadvantages of glass fibers contribute that glass based composites exhibit lower ballistic strength compared to nylon based composites, although glass fibers have both, higher tensile strength and higher sonic velocity compared to nylon fibers. Which of the above mentioned factors affecting the ballistic resistance of the composites is prevailing is very hard to say. When a bullet strikes the panel it is caught in a "web" of very strong fibers. These fibers absorb and disperse the impact energy that is transmitted to the panel from the bullet, causing the bullet to deform or "mushroom". Additional energy is absorbed by each successive layer of fabric in the panel, until the bullet has been stopped. Because the fibers work together, both, in the individual layer and with other layers of the fabric, a large area of the panel becomes involved in preventing the bullet from penetrating. This also helps in dissipating the forces which can cause nonpenetrating injuries (blunt trauma) to the internal organs. Elegant, as this simplified view of ballistic impact may be, it does not offer a clue as to how yarn properties like strength and stiffness are translated into ballistic performance, i.e. stopping power. Publications on this issue are virtually non-existent. Empirical observations are available, but there is no model that predicts ballistic performance as a function of measured fiber properties. For one thing, it is unclear whether one should look for higher strength (higher energy absorption) or for higher modulus (higher velocity of the strain wave in the fiber). Traditional fibers like melt-spun polyamide and polyester show an inverse relationship between strength and modulus. It is very difficult to improve one characteristic without affecting the other. The fiber designer therefore has to make a choice but he/she needs at least a crude theoretical model to do this. Unfortunately, for ballistic applications such model is not available [16, 17].

From the ballistic results we can now calculate the respective energies of absorption of the composites. The energy of absorption is the maximum kinetic energy a composite can withstand without being perforated and is defined as a ratio between kinetic energy of the projectile and the areal weight of the composite. Figure 4 shows the energies of absorption of the two sets of composites under investigation.

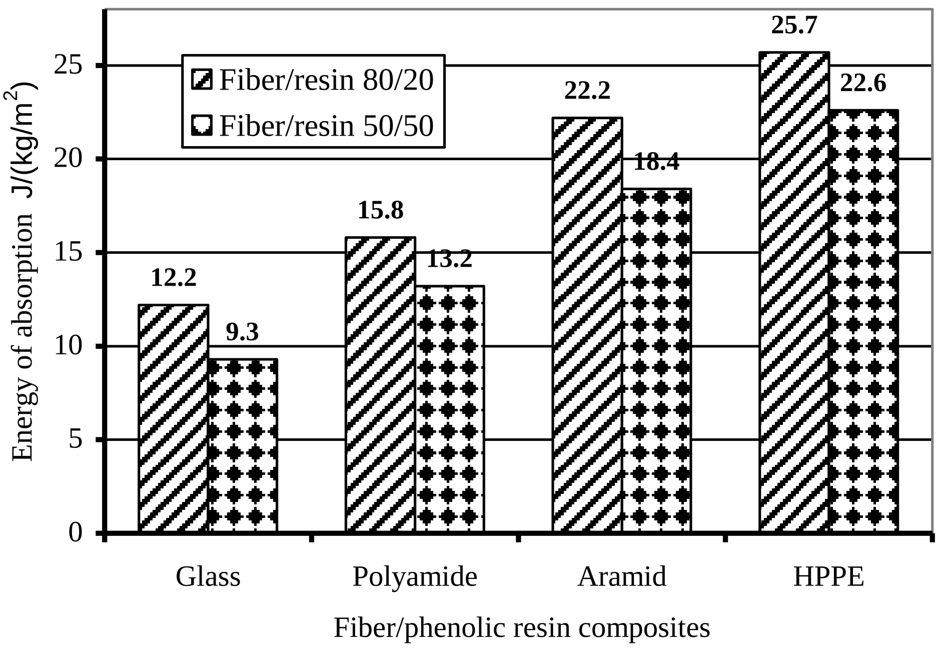

Fig. 4. Energies of absorption of composites

By applying the full factorial experimental design we can determine the ballistic strength, V_{50}, of the composites in the investigated range, as a function of the areal weight and fiber/resin ratio i.e. resin content. The experimental matrix is shown in Table 5 and the coding of variables – in Table 6.

Table 5. Experiment matrix

Test	x_1	x_2	x_1x_2	V_{50}, (m/s)			
				Glass	PA	Aramid	HPPE
1	-1	-1	+1	188.4	218.4	238.9	268.9
2	1	-1	-1	395.6	441.9	557.0	580.6
3	-1	1	-1	169.4	199.1	217.4	248.0
4	1	1	+1	336.2	405.0	504.4	545.8

Table 6. Coding of the variables

	Areal weight, kg/m^2	Resin content, %
Base level, $x_i=0$	5.5	35
Interval of variance	3.5	15
Upper level, $x_i=+1$	9	50
Lower level, $x_i=-1$	2	20
Code	x_1	x_2

The response function, y_n i.e. V_{50} as a function of areal weight (x_1) and resin content (x_2) is given by the following regression equations:

- Glass/phenolic composites:

$$y_n = 134{,}1714 + 33{,}4476 x_1 - 0{,}2486 x_2 - 0.1924 x_1 x_2 \quad (2)$$

- Nylon/phenolic composites:

$$y_n = 164{,}0571 + 33{,}6048 x_1 - 0{,}4757 x_2 - 0.0838 x_1 x_2 \quad (3)$$

- Aramid/phenolic composites:

$$y_n = 156{,}4238 + 48{,}4048 x_1 - 0{,}4205 x_2 - 0.1481 x_1 x_2 \quad (4)$$

- HPPE/phenolic composites:

$$y_n = 191{,}1286 + 45{,}8524 x_1 - 0{,}5643 x_2 - 0.0662 x_1 x_2 \quad (5)$$

4. CONCLUSION

All four composites can be applied in personal ballistic protection but with different degree of protection. On a weight basis, HPPE composites exhibit best ballistic performance, aramid based composites are second best followed by ballistic nylon composites. Glass based composites have shown the poorest ballistic resistance, due to its isotropic structure and the highest specific weight of all investigated fibers. Fiber/resin ratio is a very influencing factor in the ballistic resistance of composites. The fibers are the load bearing components in the composites and with their increase, ballistic resistance increases.

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