Original Article

Performance of jute non-woven mat reinforced polyester matrix composite in multilayered armor☆

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ABSTRACT

This paper presents results obtained through ballistic tests on multilayered armor system (MAS) using polyester composite reinforced with jute non-woven mat as second layer. Following international standard tests are carried out with ammunition 7.62×51 mm, with a velocity above of 800 m/s. The MAS is composed of a front layer with hexagonal ceramic tile (alumina doped with 4 wt% of niobia), the second layer of polyester matrix composite reinforced with 30 vol% of jute non-woven mat and the third layer an aluminum alloy plate. The utilization of polymeric composites reinforced with natural fibers to replace the aramid fabric (Kevlar^{TM}) is of interest because their performances are similar in the armor system but the composite is less expensive. Scanning electron microscopy analyses show that the polyester/jute non-woven mat composite captured ceramic fragments through mechanic incrustation. Moreover the replacement of aramid fabric for polyester matrix composites reinforced with jute non-woven mat provides weight reduction of the MAS by 5.4% and a cost reduction of 474%.

1. Introduction

A multilayered armor system (MAS) is intended to provide a lightweight and effective personal protection. Its objective is to absorb the bullet kinetic energy and prevent fragments penetration [1]. The typical MAS is composed of a front pressure-compacted ceramic or ultra-high molecular weight polyethylene (UHMWPE) with the purpose of absorbing most of the bullet impact energy by fragmentation into fine particles. A MAS second layer will absorb the remaining impact energy associated with the cloud of supersonic fragments generated in the front impact. Traditionally, aramid fabric laminates such as Kevlar^{TM} and Twaron^{TM} [2,3] as well as UHMWPE, such as Dyneema^{TM} and Spectra^{TM} [4,5], are commercial materials used as MAS second layer. Another MAS third layer, normally a ductile metallic sheet may be added to reduce even further the energy carried by the impact shock
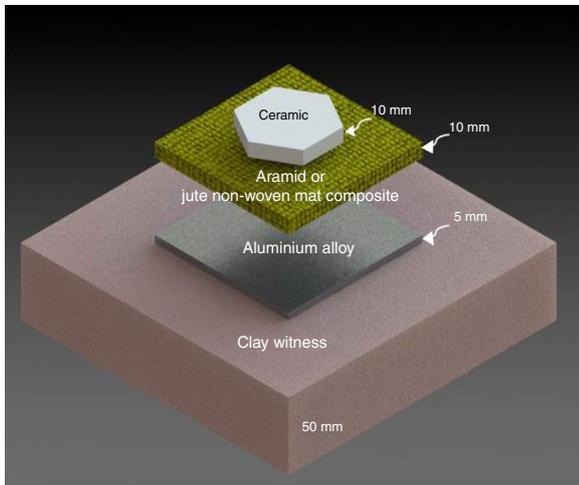
Fig. 1 – Schmatic representation of the investigated multilayered armor placed ahead of a clay witness block.
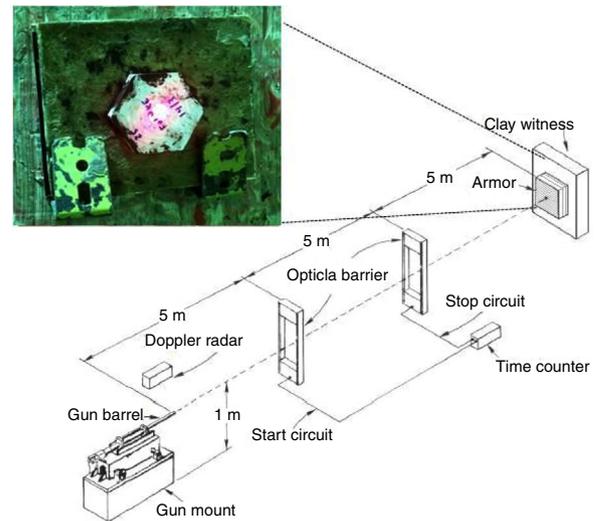

Fig. 2 – Schematic view of the ballistic facility in a CAEx shooting tunnel. Insert of anof an actual MAS ith 30 vol% jute non-woven mat reinforced polyester composite as second layer, clamped to the clay witness block in direct contact with the Al sheet, as third layer.

wave [6]. According to the American standard NIJ 0101.06 [7], the MAS has a protection level III. In other words, this system resists the impact of a high velocity projectile such as 7.62×51 mm caliber ammunition, wichi has a higher impact energy associated with a velocity above 800 m/s. In a ballistic test the MAS is set as a target with a block of so-called clay witness standing behind. This block simulates a human body to be protected by the MAS, and should only allow penetration of the fragments carried by the impact shock wave up to a standard limit of 1.73 in (44 mm) [7]. Beyond this depth of indentation in the clay witness the ballistic test causes lethal trauma to the body.

The interest in using as second layer a polymer matrix composite material reinforced with natural fibers as a substitute for synthetic fibers (Kevlar^{TM} or Dyneema^{TM} fibers) is because the material has a lower cost, is lighter and might have the same performance [8–13]. Indeed, natural fibers in addition of being lighter and cheaper are renewable, less abrasive with processing equipments and environmentally friendly [14]. The use of composites reinforced with natural fibers presents some advantages as compared with synthetic fibers such as biodegradability, low density, less abrasiveness to process equipment and low cost [15–23]. Engineering parts and industrial components mainly in vehicles fabrication [24–26] are currently using natural fibers and fabric.

In addition to natural fibers, non-woven mats based on these fibers might also be affective reinforcements for polymer composites for MAS second layer. Therefore, this work aimed to analyze the ballistic performance of MASs using, as second layer, polyester composites reinforced with 30 vol% of jute non-woven mat and compare their performances with that of a MAS using as second layer an aramid fabric laminate, commercially known as Kevlar^{TM}.

2. Experimental procedure

Multilayered armor systems (MAS) like the one, schematically shown in Fig. 1, were ballistic tests as per NIJ standard [7].

The MAS was composed of a front 10 mm tick Al_2O_3–4 wt% Nb_2O_5 hexagonal ceramic tile with 31 mm of side dimension. The very brittle ceramic tiles were fabricated by 1400 °C sintering for 3 h a mixture of pure Al_2O_3 powder, supplied by Treibacher Scheifmittel, Brazil, and intergranular precipitated Nb_2O_5 powder supplied by the "Companhia Brasileira de Mineração e Metalurgia", CBMM, Brazil. The final ceramic grain size was about 4 μm.

Bonded to the front ceramic, a $150 \times 120 \times 10$ mm composite plate second layer was produced by intercalating pieces of jute non-woven mat, supplied by the Lealtex, Brazil, with still fluid unsaturated orthophthalic polyester resin mixed with 0.5 wt% ethyl methyl ketone, as hardener, both supplied by Resinpoxy, Brazil. After laying down in a steel mold the necessary 30 vol% amount of non-woven mat and polyester for a final 10 mm thick plate, a pressure of 5 ton was applied for 24 h. A third layer of $150 \times 120 \times 5$ mm 5052 H34 aluminum alloy sheet was also bonded to complete the MAS. Bonding was done with commercial Sikaflex^{TM} glue from Sika Co (Brazil).

Ballistic tests, schematically illustrated in Fig. 2, were carried out at the "Centro de Avaliações do Exército" (CAEx), shooting range facility in the Marambaia peninsula, Rio de Janeiro, Brazil. The insert in this figure shows the actual view of 30 vol% jute non-woven mat reinforced polyester composite MAS clamped to the clay witness block and ready for the ballistic test. The clay witness block, Figs. 1 and 2, simulating a human body protected by the MAS, was placed in direct contact with the aluminum alloy sheet as MAS third layer. The special clay witness for this purpose is known as plastiline and was supplied by the Corfix firm. All ballistic tests were conducted according to the standard [7] using class III 7.62×51 mm army ammunition shot from a gun barrel located 15 m from the MAS target, Fig. 1, inside a CAEx tunnel. The 7.62 mm (9.7 g) lead bullet velocity was measured by

Fig. 3 – Depth of indentation in the clay witness measured with laser sensor caliper.

Fig. 4 – Typical aspect after ballistic test of MAS targets with second layer of 30 vol% jute non-woven mat reinforced polyester composite.

optical barriers and Doppler radar schematically represented in Fig. 2.

A total of 8 MASs with a plate of 30 vol% jute non-woven mat reinforce polyester composites, as second layer in Fig. 1, were ballistic tested. After each ballistic test, which did not completely perforated both the MAS and clay witness block, an indentation was produced in the clay. The depth of indentation duplicates the plastic deformation imposed on the aluminum sheet by the bullet impact. According to the standard [7], the measured depth of indentation is limited to 44 mm in order to avoid a lethal trauma to the MAS weaver. Measurements were performed in 10 points at deepest position for statistical analysis with a laser sensor caliper with 0.01 mm of precision, shown in Fig. 3. The Weibull statistic was used to analyze the depth of indentation results.

Fractured pieces of MAS components dispersed after ballistic test were analyzed by scanning electron microscopy (SEM) in a model Quanta FEG 250, FEI microscope operating with secondary electrons at 20 kV.

Densities and costs of MAS components were determined by using the Archimedes method and 2017 actual commercial prices, respectively. An economic analysis based on these data will be further presented.

3. Results and discussion

In all ballistic tests, conducted in this work using MAS as target, the impact energy failed to perforate the aluminum alloy third layer. This layer was plastically deformed and caused a depth of indentation in the clay witness, Fig. 3, smaller than 44 mm, with is the required limit by the NIJ standard [7]. It is important to observe the aspect of the MAS target after the ballistic tests shown in Fig. 4. In this figure one sees that the hexagonal front ceramic has disappeared by complete shattering. Moreover, in the MAS of Fig. 4, its second layer of 30 vol% of jute non-woven mat composite was only partially perforated.

Table 1 presents the average values and corresponding Weibull parameters for the measured, Fig. 4, indentation

| Table 1 – Depth of indentation for different investigated multilayered armor systems.				
MAS target with second layer	Modulus (β)	Precision (R^2)	Depth of indentation (mm)	Reference
Kevlar™	8.43	0.9	21 ± 3	[12]
30 vol% jute non-woven mat polyester composite				
MAS 1			32	
MAS 2			16	
MAS 3			24	
MAS 4			27	
MAS 5			24	
MAS 6			16	
MAS 7			34	
MAS 8			20	
Average depth of indentation	3.76	0.97	24 ± 7	PW
30 vol% sisal fiber reinforce epoxy composite			18 ± 2	[9]
30 vol% curaua fiber reinforce polyester composite			22 ± 2	[10]
30 vol% jute fabric reinforce epoxy composite			21 ± 3	[11]
30 vol% ramie fabric reinforce epoxy composite			17 ± 1	[12]
30 vol% giant bamboo fiber reinforce epoxy composite			18 ± 2	[13]

PW, present work.
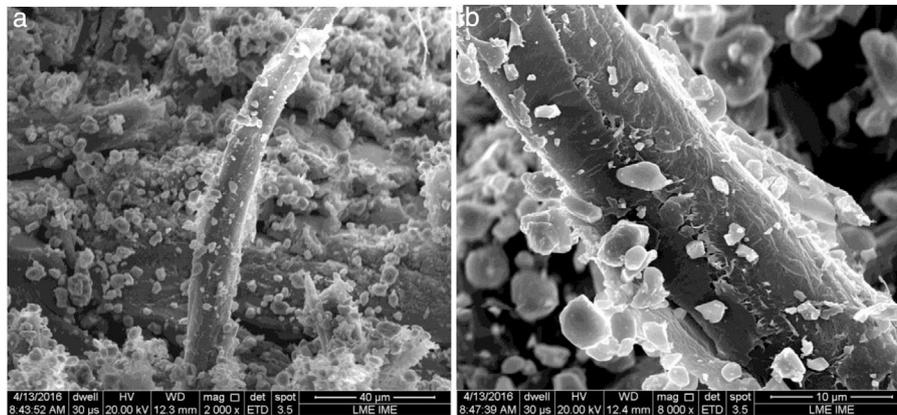
Fig. 5 – SEM fractographs of the fracture surface of a 30 vol% jute non-woven mat composite covered with ceramic fragments: (a) low magnification; (b) high magnification of jute microfibrils.
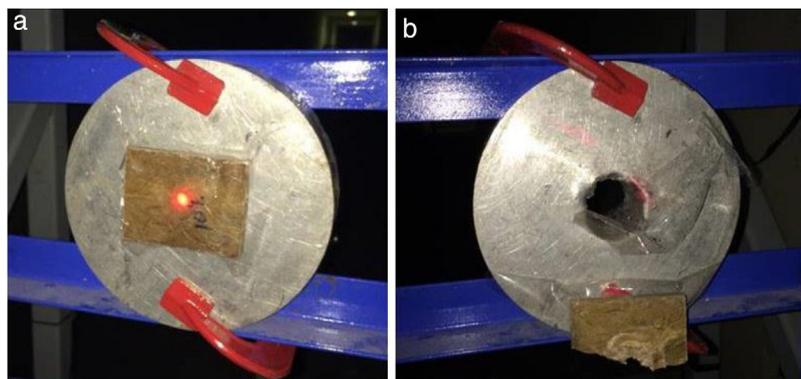

Fig. 6 – Ballistic test to measure the impact and residual velocities after perforation of a jute non-woven mat composite plate.

depths on the clay witness for the 8 MASs including that for similar MAS with Kevlar™ as second layer, which was also previously reported [8–13] for other natural fiber/fabric composites.

The results of average depth of indentation in Table 1 are, within the error, practically equal to that of Kevlar™. In fact, within the corresponding standard deviations, the indentation value for the composite, 24 ± 7 mm, and for the Kevlar™, 21 ± 3 mm, might statistically be considered similar. Similar results were also found for other natural fiber/fabric [8–13] and Kevlar™ as second layer of MASs with same dimensions, Fig. 1. The reason for this similar ballistic performance is the ability of the second layer, in a MAS with front ceramic, to collect fragments generated from the ballistic impact [1]. This ability does not require stronger fibers but mechanisms of mechanical incrustation as well as fragment attraction by van der Waals forces and static charges on the fiber surface, either synthetic Kevlar™ [1] or natural jute fabric [11]. Fig. 5 shows SEM fractographs illustrating the mechanism of fragments (white particles) capture by the 30 vol% jute non-woven mat reinforced polyester composite as MAS second layer.

With the purpose of a supplementary evaluation, the impact energy dissipation by each jute non-woven mat composite alone i.e., separated from the MAS, ballistic tests were carried out with a composite plate in front of a cylindrical metallic block with a hole. In these tests the velocities of the 7.62 bullet, before and after perforation of the composite plate were measured. These impact velocity, v_i, and residual velocity, v_r, allow the calculation of the energy ΔE_d dissipated inside the composite

$$\Delta E_d = \frac{1}{2}m(v_i^2 - v_r^2) \tag{2}$$

Where $m = 9.7$ g is the lead bullet mass.

Fig. 6 shows a typical test for residual velocity in a plate of 30 vol% jute fabric-reinforced polyester composite. In Fig. 6a, the plate is placed in front of the hole before the ballistic test. After the test a hole is shown in the plate, Fig. 6b, due to the bullet perforation. Part of the perforated composite plate is also shown in Fig. 6b.

Table 2 presents the impact and residual velocities as well as the internally dissipated energy, Eq. (2), from ballistic tests of individual jute non-woven mat composites. In this table, it is also presented results from the Al_2O_3–4 wt%Nb_2O_5 ceramic and Kevlar™ obtained elsewhere [11]. One should notice in Table 3 that more than 50% of the energy dissipation occurred in the ceramic, which agrees with previously reported results [1]. By contrast, individually, the other MAS components dissipate less than 7% of the bullet energy each one. In particular, the Kevlar™ dissipates a relatively low amount of energy as compared to the jute non-woven mat composites. To some

Table 2 – Impact and residual velocities together with internally dissipated energy in individually ballistic teste MAS components.

MAS component	V_i (m/s)	V_r (m/s)	E (kJ)	ΔE_d (%)	Reference
Al_2O_3 ceramic	848 ± 6	567 ± 43	1.60 ± 0.300	54.1	[11]
30 vol% jute non-woven mat polyester composite	844 ± 6	810 ± 9	0.25 ± 0.008	6.9	PW
Kevlar™	848 ± 6	841 ± 7	0.06 ± 0.001	1.7	[1]

PW, present work.

Table 3 – Evaluation of weight and cost of the different multilayered armor components.

Armor component	Volume (cm^3)	Density (g/cm^3)	Weight (kgf)	Price per kg (U$ dollars)	Component cost (U$ dollars)
Ceramic ($Al_2O_3 + 4\%$ Nb_2O_5)	190	3.72	0.707	2.18	1.54
Kevlar™	190	1.44	0.274	63.60	17.43
Polyester-30 vol% Jute non-woven mat	190	1.16[a]	0.220	3.10[b]	0.68
Aluminum 5052-H34	95	2.68	0.255	5.10	1.30
Epoxy-30 vol% jute fabric	190	1.13	0.215	8.38	1.80
Total weight with Kevlar™ (kgf)		1.236	Total cost with Kevlar™		20.27
Total weight with Polyester-30 vol% Jute non-woven mat		1.182	Total cost with Polyester-30 vol% jute non-woven mat		3.53
Total weight with Epoxy-30 vol% Jute non-woven mat		1.177	Total cost with epoxy-30 vol% Jute fabric		4.64
Decrease in weight (%) of MAS with jute non-woven mat composite as compared to Kevlar™		5.400	Decrease in cost (%) of MAS with jute non-woven mat composite as compared Kevlar™		474
Decrease in weight (%) of MAS with jute non-woven mat composite as compared to Epoxy-Jute fabric		0.42	Decrease in weight (%) of MAS with jute non-woven mat composite as compared to epoxy–jute fabric		31.44

[a] Jute fibers: $1.3 \, g/cm^3$; polyester resin: $1.1 \, g/cm^3$.
[b] Jute fibers: US$ 0.3; polyester resin: US$ 4.3.

extend, these results are coherent with those in Table 1, where Kevlar™ has comparable ballistic performance to the jute non-woven mat reinforced polyester composites in terms of depth of indentation.

The relatively low energy dissipation by the Kevlar™ alone in Table 2 is a consequence of the high ammunition used in the test. A sharp-pointed 7.62 mm projectile penetrates easily between the aramid fibers in the Kevlar™. This causes breaking and stretching as well as separation and pullout of the fibers. However, the front ceramic in the MAS is reduced to fragments after the bullet impact. In this case both Kevlar™ and natural fiber/fabric composites, as MAS second layer, are efficient barriers to the remaining ballistic energy by capturing the fragments [1,8–13].

Table 3 presents an economic analysis based on weight and cost of the several MAS. The results in this table are based on laboratory measured densities and 2017 prices provided by the suppliers. For calculation purpose, the face area of the ceramic was considered as 150×120 mm, similar to the other MAS components, and not the smaller hexagonal tile is in Figs. 2 and 3.

The results presented in Table 3 indicate that the use of 30 vol% jute non-woven mat reinforced polyester composite corresponds to about 474% of reduction in cost as compared with Kevlar™ used as MAS second layer. Moreover, the same composite is 31.44% cheaper than the similar 30 vol% jute fabric-reinforced epoxy composite [11].

As for the weight reduction only a relatively small percentage, less than 5%, is obtained in MAS with 30 vol% jute non-woven mat composite as second layer, in comparison to MAS with Kevlar™. Although Kevlar™ and jute non-woven mat composite in Table 1 display practically the same ballistic performance, the cost saving in Table 3 supports the replacement of Kevlar™ for any jute non-woven mat composite. In addition to this economical advantage, jute non-woven mat composites are also associated with environmental and societal benefits [19]. Nowadays, these advantages contribute to a practical indication that armor vests using 30 vol% of jute non-woven mat composite as MAS second layer is more advantageous than Kevlar™.

4. Conclusions

- Jute non-woven mat reinforced polyester composite, used as second layer of a multilayered armor system (MAS) with front ceramic and backed by aluminum alloy sheet, attended the international ballistic standard.
- The depth of indentation in a clay witness simulating a human body protection with a MAS against high velocity 7.62 mm bullet was, within statistical precision, the same in both jute non-woven mat composites and Kevlar™ as MAS second layers.

- Mechanisms of ceramic and bullet fragments capture are equally efficient for Kevlar^{TM} and jute non-woven mat composite. This is also verified in the values obtained for internally dissipated energy.
- In spite of similar ballistic performance and only slight difference in weight, the much lower cost of the 30 vol% jute non-woven mat reinforced polyester composite justify its substitution for Kevlar^{TM}.

Conflicts of interest

The authors declare no conflicts of interest.

Acknowledgements

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