MECHANICAL AND IMPACT CHARACTERISATION OF HYBRID COMPOSITE LAMINATES BASED ON FLAX, HEMP, BASALT AND GLASS FIBERS PRODUCED BY VACUUM INFUSION

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Keywords: hybrid laminates, impact properties, natural fibers, basalt

Abstract
This work concerns the production by vacuum infusion and the comparison of the properties of different hybrid composite laminates, based on glass, flax and hemp fibers in different combinations, keeping constant basalt laminates as the inner core of the layered material and a 21±1% fibers volume throughout. The laminates have been subjected to tensile, flexural and falling weight impact tests. Mechanical tests show quite limited differences between the three hybrid configurations, a fact which is also suggested by the not large variation in material density obtained. The main differences have been observed dealing with falling weight properties, carried out at energies between 6 and 24 Joules using a half-inch impactor with a mass of 1.25 kg. Here, the hybrid configuration containing together flax and hemp fibers shows some energy dissipation properties with the onset of complex damage modes in the laminate.

1 Introduction

Hybridization is a commonly used procedure to obtain properties, which are intermediate between the two originating materials. Dealing with impact properties of polymer composites, hybridization may result in a compromise between the manufacture of a more sustainable material, and the as close as possible preservation of the properties of the original composite material, usually based on E-glass fibers. A number of studies have been performed recently, which suggest that mechanical and impact properties can be possibly tailored using hybridization basing on glass or basalt fiber laminates and including other natural fibers [1-3]. In particular, with respect to plant fibers, which equally show thermal and acoustic insulation properties, the higher specific weight of basalt fibers (around 2700 kg/m^3) is widely compensated by their higher modulus, excellent heat resistance, good resistance to chemical attack and low water absorption [4]. This suggests that hybrids laminates, based on basalt fibers and plant fibers and/or glass-plant fiber hybrid laminates, the latter being particularly studied when it comes to the need for sufficient impact resistance [5], may have some interest. This would possibly result in a more sustainable end-of-life scenario without substantially affecting the structural performance of the laminates.

2 Materials and testing methods

The resin system used was an EC 360 (resin)/W160 (hardener) epoxy, provided by Elantas Camattini s.p.a. The reinforcements based on flax (surface density 300 g/m²), hemp (300 g/m²), and the basalt grid (240 g/m²), were all provided by Fidia Srl, while the glass mat (100 g/m²) has been provided by G. Angeloni Srl.

All the composite panels have been produced by means of a vacuum infusion process, whose layout is given in Figure 1. For this purpose, for each kind of panels, a stack of dry reinforcement plies has been laminated over a glass mould. After the lamination stage, the layout has been completed with the flow media and the infusion network, and finally the mould has been sealed with the vacuum bag. The curing stage of the resin, after the infusion is concluded, has been carried out at room temperature, while the post curing took place in an oven in two sub-stages: at 60°C for three hours and subsequently at 80°C for four hours. The in-mould pressure measured during the infusion stages was equal to 20 mbar. Vacmobiles model 20/2 vacuum pump, provided by Vacmobiles Europe by Filter Technics has been used.

Rectangular 260 mm x 450 mm sheets have been obtained. Subsequent cutting operations have been carried out with the aim to produce specimens suitable for mechanical characterization, in accordance to the related standards.

Three laminates were based on hemp, flax and basalt fibers respectively, which were used for comparison with the three hybrids schematized in Figure 2.

In particular, the following stacking sequences have been followed:

Hemp, flax and basalt laminates have all been produced by stacking together 4 layers of biaxial textiles, according to a [0/90]2S lay-out. Fiber volume fraction is was (20.16 ± 1,37) % for hemp; (24.82 ± 0,83) % for flax; for (28.23 ± 0,85)% for basalt.

GFB laminate: total fiber volume fraction equal to (21.18 ± 0.32) %, of which flax 11.72 (± 0,18) %, basalt (7.16 ± 0,11) % and glass (2.30 ± 0,04) %.

GHB laminate: total fiber volume fraction (22.53 ± 0.48) %, of which hemp (8.56 ± 0.16) %, basalt (11,38 ± 0,21) % and glass (2,59 ± 0,05) %;

FHB laminate: total fiber volume fraction (21.18 ± 0.32) %, of which flax (9.11 ± 0.20), hemp (7.85 ± 0,12) % and basalt (5,57 ± 0,05)%;

For all hybrids, the fiber direction into each textile network is 0/90.

Mechanical testing

Specimens cut from the above-mentioned sheets of planar dimensions 200x20 mm have been subjected to tensile test, according to the standard ASTM D 3039, using as a mechanical testing machine a dynamometer, INSTRON model 3382. A load cell of 100 kN has been used and a testing speed of 5 mm/min has been applied to the specimens.

Five samples for each sheets main directions have been tested (longitudinal and transverse or according respectively the warp and weft direction of the textile).

The same procedure has been used also in the case of the flexural test, carried out on the samples. The dimensions were the same and a span of 120 mm was used.

In this case, as a mechanical testing machine, a dynamometer, LLOYD model 30K, has been employed. As a reference standard, the ASTM D790 has been taken into account and a testing speed of 1.7 mm/min has been set. The tensile and flexural modulus has been measured by fitting all the points between 20 and 80% of the maximum load, considering that the mechanical behavior of the laminates shows no clear yielding points.

Impact testing

Impact tests were carried out using an in-house built drop-weight impact tower. The impactor diameter was 12.7 mm and its mass was 1.25 kg: this is set to be dropped from a maximum height of 3.3 meters (which is equivalent, given the applied mass, to a theoretical energy of approximately 40 Joules). Sampling frequency of the signals was 100 kHz with no external filtering.

The variables measured on the drop-weight tower were: contact force, measured using a piezoelectric load-cell for dynamical loading; velocity, measured through elaboration of the signal supplied by a Laser sensor, placed about 5 cm above the quote of the sample; impactor speed and position as a function of time, obtained by double numerical integration of force signal (as suggested by ASTM D-7136 standard).

In this work, 100 mm side panels were impacted at energies from 6 to 24 Joules, the impactor being dropped from height of 0.5 to 2 meters.

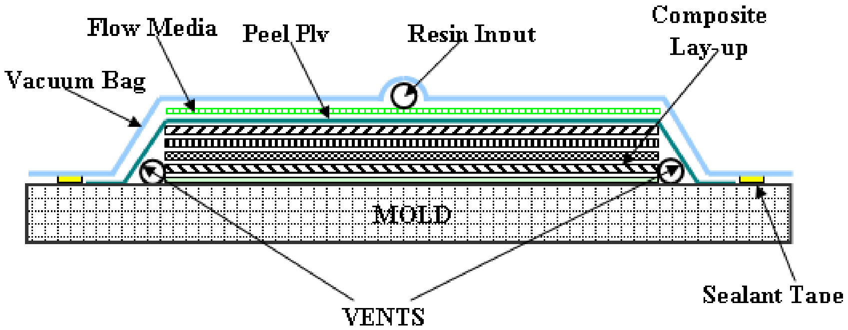

Figure 1. Lay out of the infusion stage

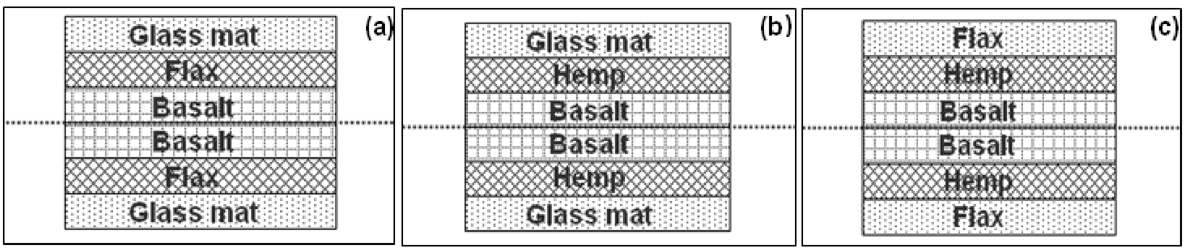

Figure 2. Layout of the hybrid composites based on glass, flax and basalt fibers (GFB) (a); glass, hemp and basalt fibers (GHB) (b); flax, hemp and basalt fibers (FHB) (c)

3. Results and discussion

The results were analyzed especially in the view of comparing the three hybrids having all basalt fiber laminates as their core. The fabrication of hybrids with plant fibers can be recommended in that it brings to a significant weight reduction, as shown in Table 1. It can be noticed that the low areal weight of the glass mat used results in a slightly lower density for the GHB and GFB laminates than for the FHB.

As expected, the basalt based composite showed the best mechanical performance over all the hybrids, which in turn performed better than laminates based on flax and hemp fibers. Comparing the three hybrids among them, it is significant to note that, as regards tensile strength results, reported in Table 2, the two hybrids including also glass fiber laminates (GFB and GHB) show superior properties than the FHB one. In terms of stiffness, the worst performance among hybrids is revealed by GHB. In addition, as observable in Figure 3 and 4, the initial slope of the tensile and flexural curves is lower for GHB than for FHB hybrids. In contrast, at higher strains the situation appears to be reversed. Flexural strength results also indicate a considerably better performance of the FHB hybrid with respect to the other two, while flexural modulus results substantially match tensile modulus ones. It can be therefore suggested that whenever a higher flexural strength with reduced weight is desired, the introduction of plant fibers in the hybrid laminate can be recommended.

Material	Apparent Density (g/cm^3)
Flax	1.20 ± 0.04
Hemp	1.18 ± 0.03
Basalt	1.59 ± 0.04
GFB	1.31 ± 0.02
FHB	1.37 ± 0.05
GHB	1.27 ± 0.04

Table 1. Materials apparent density

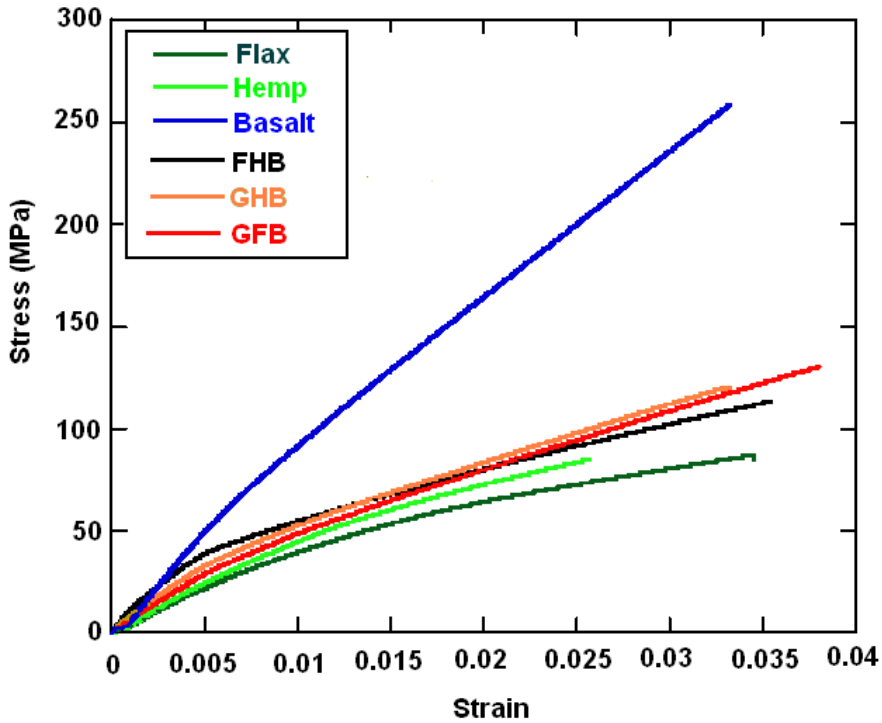

Figure 3. Typical tensile stress-strain diagrams

Laminate	Stress (MPa)	Strain	Modulus (GPa)
Flax (F)	89.03 ± 3.57	(3.45 ± 0.11)*10^{-2}	6.29 ± 0.41
Hemp (H)	79.72 ± 8.64	(2.68 ± 0.19)*10^{-2}	5.97 ± 0.35
Basalt (B)	267.54 ± 31.83	(3.33 ± 0.39)*10^{-2}	15.86 ± 1.10
FHB	115.97 ± 3.77	(3.30 ± 0.25)*10^{-2}	7.69 ± 0.63
GHB	128.84 ± 8.70	(3.50 ± 0.24)*10^{-2}	6.64 ± 0.49
GFB	153.16 ± 17.41	(3.03 ± 0.15)*10^{-2}	8.11 ± 0.60

Table 2. Tensile properties of the laminates

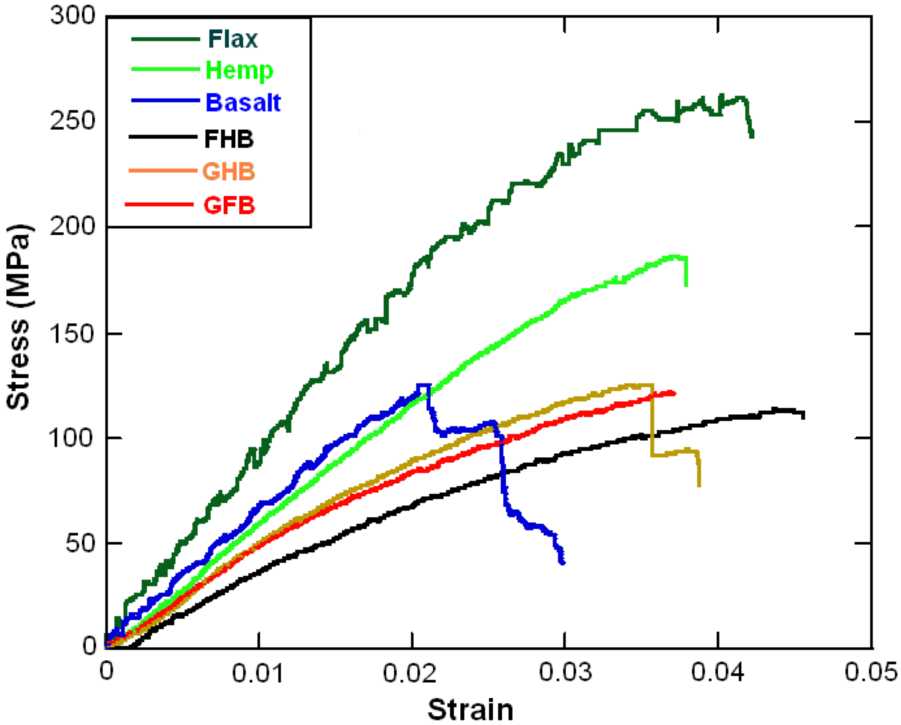

Figure 4. Typical flexural stress-strain diagrams

Laminate	Stress (MPa)	Strain	Modulus (GPa)
Flax (F)	119.97 ± 4.62	(8.83 ± 1.45)*10^{-2}	5.32 ± 0.56
Hemp (H)	99.18 ± 14.08	(6.74 ± 0.90)*10^{-2}	5.35 ± 0.74
Basalt (B)	249.36 ± 29.86	(5.15 ± 0.10)*10^{-2}	10.26 ± 0.58
FHB	208.46 ± 29.14	(5.44 ± 1.40)*10^{-2}	7.45 ± 0.,67
GHB	126.22 ± 13.63	(3.79 ± 0.06)*10^{-2}	5.90 ± 0.42
GFB	137.95 ± 19.85	(2.00 ± 0.33)*10^{-2}	8.02 ± 0.68

Table 3. Flexural properties of the laminates

In impact-damaged laminates, the effect of glass mat surface layers is perceivable in concentrating impact damage with respect to the configurations having plant fiber laminates as surface layers, reducing tearing of the back surface: this is perceivable both in Figure 5, comparing GFB and FHB, and in Figure 6, comparing hemp fiber laminates and GHB. In contrast, FHB laminate (Figure 5) shows complex cracking modes at rear, which suggest a higher potential for energy dissipation.

Falling weight impact properties were also examined from the analysis of impact hysteresis cycles (force vs. displacement). This is a common practice to take into account the different components of the energy absorbed by the material, namely elastic, plastic and damping energy, as suggested in [6]. In addition, the slope of the quasi-linear part (up to reaching the maximum load) of the force vs. displacement plot, frequently referred to as *linear stiffness,* allows comparison between different laminate configurations, provided they are both impacted with the same mass and indentor [7]. In this analysis, the linear stiffness is normalized by dividing it by the laminate thickness.

In addition, the analysis of hysteresis cycles (Figures 7 and 8 and Table 4 and 5) offers a number of suggestions about impact behavior. In particular, GFB hybrids appear only slightly superior to FHB hybrids at energies lower than penetration, such as at 12 Joules, considering also that an impact at 24 Joules does result in penetration of the latter laminates and not of the former. In contrast, the difference between hemp fiber reinforced laminates and GHB hybrids is more evident, especially at low impact energies, although they are both considerably less impact-resistant than the previous two laminates.

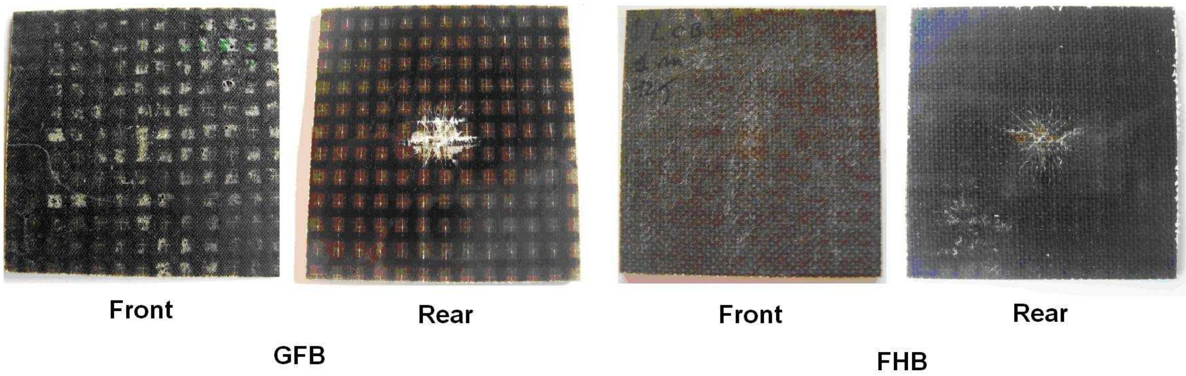

Figure 5. GFB and FHB hybrid composites impacted at 12 Joules

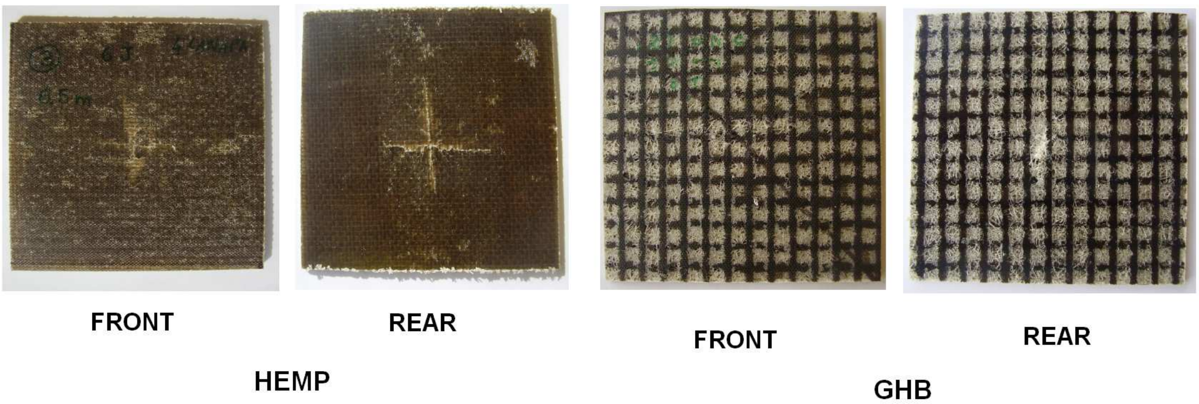

Figure 6. Hemp laminates and GHB hybrid laminates impacted at 6 Joules

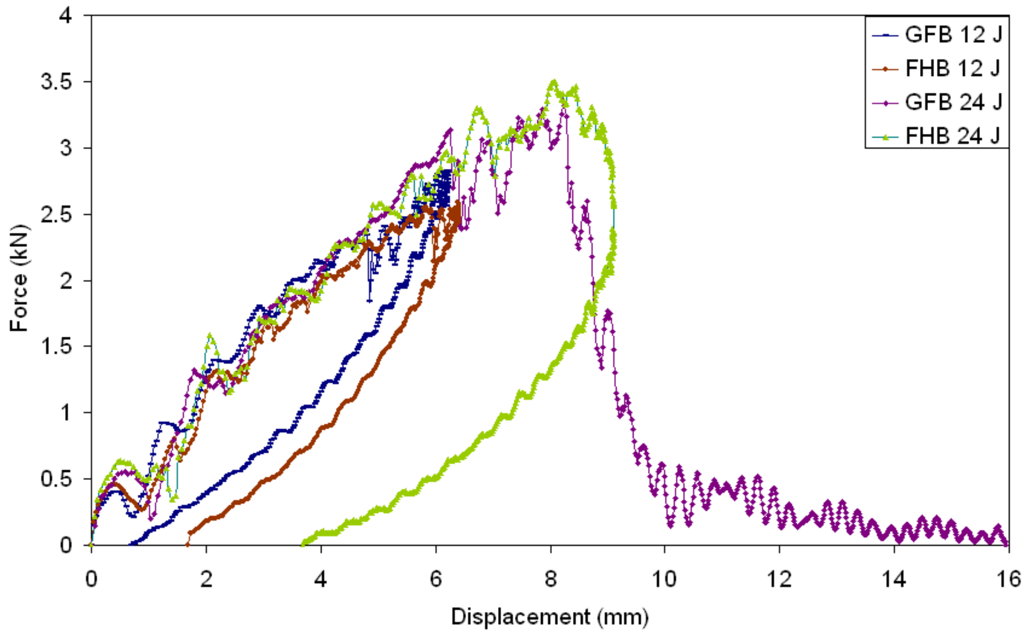

Figure 7. Impact hysteresis curves relative to GFB and FHB hybrid laminates

Laminate	Impact energy (J)	Normalized linear stiffness (N/mm)/mm	Peak load (N)
GFB	12	158	2826
FHB	12	136	2587
GFB	24	132	3352
FHB	24	130	3497

Table 4. Compared data from impact hysteresis cycles for GFB and FHB hybrid laminates

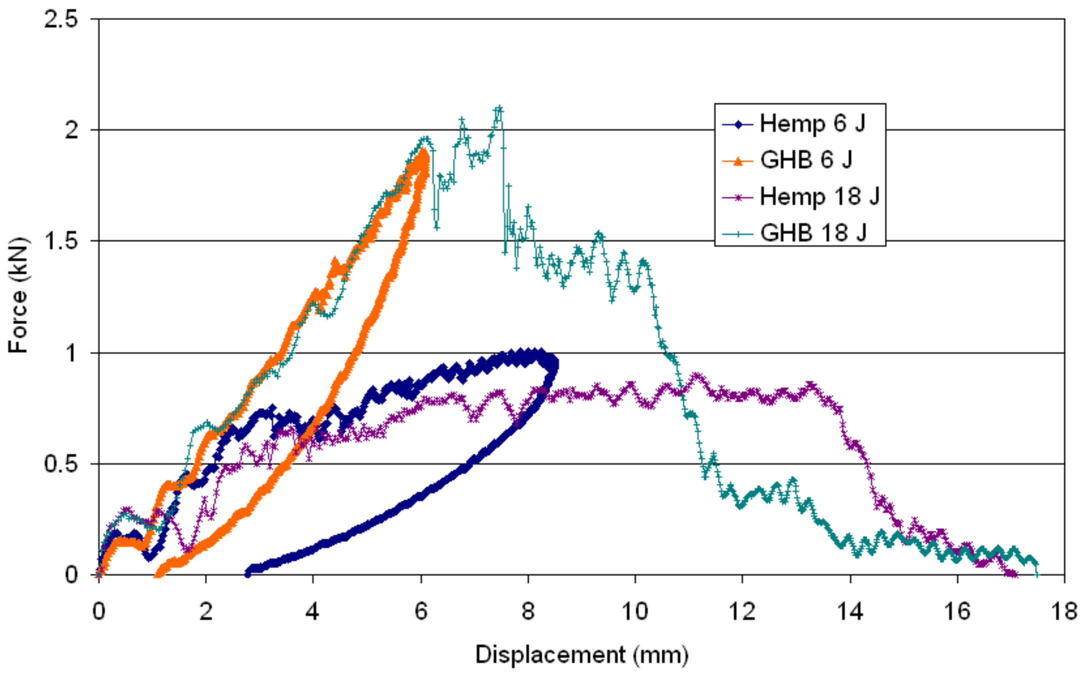

Figure 8. Impact hysteresis curves relative to hemp laminates and GHB hybrid laminates

Laminate	Impact energy (J)	Normalized linear stiffness (N/mm)/mm	Peak load (N)
Hemp	6	58	1001
GHB	6	82	1907
Hemp	18	50	897
GHB	18	55	2098

Table 5. Compared data from impact hysteresis cycles for hemp and GHB hybrid laminates

CONCLUSIONS

The study of ternary hybrid laminates, with a basalt fiber core, proved interesting to suggest which combinations of the three reinforcements, glass and two plant fibers, hemp and flax, performed better in tensile, flexural and falling weight impact tests. The indications provided suggest that the best combination is glass/flax/basalt, although the differences are quite limited in quasi-static properties and more substantial in falling weight impact properties, being clearly apparent from the analysis of hysteresis cycles. More in general, the insertion of glass fiber laminates in the hybrids reduced the tendency of plant fiber laminates to shear-induced tearing following the impact event, while the flax/hemp/basalt hybrid laminate was interesting for the onset of complex damage modes.

References

[1] Arbelaiz A., Fernández B., Cantero G., Llano-Ponte R., Valea A., Mondragon I. Mechanical properties of flax fibre/polypropylene composites. Influence of fibre/matrix modification and glass fibre hybridization, *Composites Part A* **36,** pp. 1637-1644, 2005.
[2] Santulli C., Janssen M., Jeronimidis G., Partial replacement of E-glass fibres with flax fibres in composites and effect on falling weight impact performance, *Journal of Materials Science* **40**, 3581-3585, 2005.
[3] Dehkordi M.T., Nosraty H., Shokrieh M.M., Minak G., Ghelli D. Low velocity impact properties of intraply hybrid composites based on basalt and nylon, woven fabrics. *Materials and Design* **31**, 3835–3844, 2010.
[4] De Rosa I.M., Marra F., Pulci G., Santulli C., Sarasini F., Tirillò J., Valente M. Post-impact mechanical characterisation of E-glass/basalt woven fabric interply hybrid laminates. *Express Polymer Letters* **5**, 449–459, 2011.
[5] Santulli C., Review. Impact properties of glass/plant fibre hybrid laminates, *Journal of Materials Science* **42**, 3699-3707, 2007.
[6] Santulli C., Study of impact hysteresis curves on E-glass reinforced polypropylene laminates, *Journal of Materials Science Letters,* **22,** 1557-1562, 2003.
[7] Benevolenski O.I, Karger-Kocsis J., Mieck K.P., Reubmann T., Instrumented perforation impact response of polypropylene composites with hybrid reinforcement flax/glass and flax/cellulose fibers, *Journal of Thermoplastic Composite Materials,* **13** 481-496, 2000.