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Manufacturing of composite materials with high environmental efficiency using epoxy resin of renewable origin and permeable light cores for vacuum-assisted infusion molding

Fabricación de materiales compuestos de alto rendimiento medioambiental con resina epoxi de origen renovable y núcleos ligeros permeables para infusión asistida por vacío

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Abstract

This work focuses on the manufacturing and characterization of novel and lightweight hybrid sandwich-type structures, using different stacking sequences of flax and basalt fabrics as reinforcement fibers, both of them previously silanized. To reduce the overall weight and facilitate the manufacturing process, a polyester non-woven core, was used which, besides reducing the weight of the composite it also acts as a media to spread the resin. These composites were manufactured with a partially bio-based epoxy resin with a reactive diluent derived from epoxidized vegetable oils that contributes to a 31 % of biobased content. The hybrid composites were obtained by vacuum-assisted resin infusion moulding (VARIM), where the core was used as a media to spread the resin. The mechanical properties were evaluated in flexural and impact conditions.

Resumen

Este trabajo se centra en la fabricación y caracterización de nuevos materiales tipo sándwich híbridos de bajo peso, con diferentes configuraciones de apilamiento de refuerzo de basalto y lino tratadas previamente con silanos. Para aligerar el peso y facilitar la fabricación, se empleó un núcleo de poliéster no tejido que, además de aligerar el peso del compuesto también actuó como medio de difusión de la resina. Se empleó una resina epoxi de origen parcialmente renovable con un diluyente reactivo derivado de aceites vegetales epoxidados que contribuye a un 31 % de origen renovable. Los compuestos híbridos se fabricaron mediante moldeado por infusión de resina asistida por vacío (VARIM), donde el núcleo se utilizó como medio de infusión de la resina. Las propiedades mecánicas se evaluaron en condiciones de impacto y de flexión.

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The interactions in the fiber-matrix interface were studied through field emission scanning electron microscopy (FESEM). The obtained data revealed that the silane (coupling agent) treatment works better on basalt fibers than on flax fibers, resulting in superior flexural properties on structures where these fibers are present. It is noteworthy to mention that the stacking sequence of plies directly influences the flexural properties, but it does not significantly affect the energy absorbed when these composites work on impact conditions.

Keywords: Hybrid composite materials; non-woven cores; silane coupling agents; VARIM process, basalt fibers; flax fibers.

La interacción en la interfaz fibra-matriz se evaluó por medio de microscopía electrónica de barrido de emisión de campo (FESEM). Los datos revelaron que el tratamiento de silanos funciona mejor en las fibras de basalto que en las fibras de lino, resultando en propiedades a flexión superiores en las estructuras donde estas fibras están presentes. Cabe mencionar que la distribución de apilamiento influye directamente en las propiedades a flexión, pero no afecta en la absorción de energía en condiciones de impacto.

Palabras clave: materiales compuestos híbridos, núcleo no tejidos, agentes de acoplamiento de silano, VARIM, fibras de basalto, fibras de lino.

1. Introduction

The use of composite polymeric materials has increased considerably in our lives not only in technical applications but in everyday applications. This is due to their ability to tailor the desired properties [1]. Thermosetting matrices such as unsaturated polyester resins (UP), epoxies (EP), phenolics (PF) [2–4], among others, and reinforcing fibers such as carbon (CF), aramid (AF), and glass (GF) are the most used due to the high mechanical properties they can provide together with very low weights that make them suitable for automotive, sports, ballistic, civil construction applicatiozns among others [5–9]. Despite this, the conventional high-performance fibers offer some disadvantages. Among others, a critical drawback of these fibers is related to the production costs and conditions as, for example, CF requires extremely high temperatures to obtain highly purified fibers. On the other hand, these conventional reinforcing fibers have a substantial environmental impact, related to the production stages and the problematics after their useful life; this means that their mass production is practically unfeasible [10, 11].

Matrices based on epoxy resins are the most used, due to excellent mechanical, thermal, and coating properties that provide to composite materials. This is generally achieved by the functional groups that are found in its structure, namely epoxy/oxirane rings which can polymerize to form 3D net structures. Most of the currently available epoxy resins are based on diglycidyl ether of bisphenol A (DGEBA), which comes from the reaction of epichlorohydrin and bisphenol A (BPA) [12]. These components are petroleum-derived materials and, like synthetic fibers have a considerable impact on the increase in the carbon footprint. In order to develop composite materials with low or restricted environmental impact, research studies have been carried out in both components, i.e. the thermosetting matrix and the reinforcing fibers [13]. Traditional epoxies are bioderived as above-mentioned, but in the last decades, new epoxies have been industrially manufactured from renewable resources thus contributing to lowering the overall carbon footprint

This type of resins is characterized by the fact that part of its content is obtained from renewable resources, unlike conventional resins obtained from petroleum derivatives. Vegetable oils (VOs) have gained high relevance due to their potential in manufacturing bio-based materials [14, 15]. The basic structure of these vegetable oils is based on a triglyceride structure composed of three different fatty acids chemically attached to a glycerol skeleton. Some of these fatty acids, such as oleic, linoleic, and linolenic acids, contain one, two and three unsaturated carbons, respectively, and this allows selective modification of VOs with different chemical functionalities. VO's can be epoxidized, maleinized, hydroxylated, acrylated, and so on to give partially bio-based resins. These "eco-friendly" resins have been developed in such a way that their mechanical and thermal properties are similar to their petrochemical counterparts so that they can compete with petroleum-derived thermosetting resins with the additional feature of the renewable origin [13].

An alternative to the use of synthetic and rock-wool fibers in the manufacturing of high-performance composite materials is to replace fully or partially some of these fibers and/or fabrics with natural fibers. Several researchers have focused their research on developing hybrid composite materials with conventional and natural fibers. Natural fibers such as hemp, flax, palm leaf are the most used and offer interesting, balanced properties [16, 17]. One fiber that stands out for its excellent mechanical properties, due to its composition and structure is flax [9]. Nevertheless, all-flax composites cannot compete with high-performance composite materials. That is why the manufacturing of hybrid composite structures has become an interesting alternative to find a balance between environmental concerns and technical properties.

As natural fibers cannot compete with high-tech fibers such as carbon or aramids, it is quite common to combine natural fibers with mineral fibers, which are cost-effective compared to high tech fibers. Basalt fibers have been used in thermoplastics and thermosetting composite materials as an alternative to glass fiber. These fibers are obtained from basalt rocks, which is one of the most abundant on the earth's surface. Its structure is quite similar to glass fiber but with different silica and alumina content. Unlike glass fiber, the production process of basalt fiber is simpler, more efficient and does not generate waste due to the simple structure. Barouni and Dhakal [18] have developed flax/glass hybrid composites with improvement in the impact damage characteristics due to the capability to absorb the impact energy of flax fibers. On the other hand, Mazur ¿emphet al. [19] studied the hybrid effect of composites based on basalt and carbon fibers, where an increase in the strength and tensile modulus was reported when the shared mass of the fibers was about 7 wt%.

Among the hybrid composite materials, it is worthy to note the interest on sandwich panels. These have been used in areas where larger thicknesses, lightweights, high rigidity, and insulation capacity are required. They are generally used in the construction, automotive, aircraft areas, and so on, due to their extraordinary ability to support flexural (out-of-the-plane) forces [20]. Sandwich panels are composed of two outer sheets (face sheets) and a core that generally has lower properties than the face sheets but it contributes to support the out-of-plane forces by shear with the outer sheets.

The face sheets are usually composite laminates with several layers with fabrics oriented in different directions to improve the isotropy behaviour [21]. These face sheets often consist of unsaturated polyester (UP) sheets with glass fibers (GF) for applications with moderate mechanical performance, or epoxy (EP) plies with carbon fibers (CF) and/or aramid (AF) for applications with high mechanical responsibility [22, 23]. The core is usually made of materials with low density and relatively poor mechanical characteristics, since their purpose is not to support mechanical resistance. Core materials offer high lightness and a very good capacity of shear stresses absorption. Some of the widely used cores include balsa wood, polyurethane, or honeycomb structures [24–26]. Manufacturing of composite sandwich panels usually is carried out by hand layup and vacuum bagging.

In the recent years some research has been focused on the development of cores which are not only a part of the sandwich panel but also, can contribute to improve manufacturing processes. Vacuum assisted resin infusion moulding (VARIM) is a very widely used technique alternative to the industrial resin transfer moulding (RTM) to obtain composite materials with excellent balanced properties in a simple way. Nevertheless, the VARIM process requires different consumables (infusion nozzle, bleeding web, spiral tube, and so on), and it is not the best manufacturing process for sandwich panels since the typical cores do not transfer the infused resin. Recently, new cores have been developed with multifunctional features.

On the one hand, they can act as core materials in sandwich structures, but on the other hand, they offer enough porosity to enhance resin infusion through it. Some of these cores are composed of a cell structure separated by channels with synthetic microspheres, which do not absorb resin; this channel helps the resin flow through the composite material [27]. Chatys *et al.* [28] have used Lantor Soric® in carbon fiber sandwich composites to manufacture car safety bumpers due to its flexibility and the ability to absorb impact energy compared to conventional metal parts. Eum *et al.* [29] have reported that using the core as an infusion media in a conventional VARTM process, it is possible to provide similar properties to similar composites since this does not catch resin and helps to the correct its flow.

Hybrid composite materials, due to the diverse nature of their components, do not usually have the required synergy, since the stresses are not correctly transferred to the reinforcement fibers, which are generally the most resistant material. In general, to improve the interface interaction between fibers and the resin, several methods have been developed. The most used method is chemical treatment with tailored silanes. Silanes offer dual functionality, thus allowing them to react firstly with the fiber surface, and during the crosslinking, they can react with the resin, thus leading to real chemical bridges between the thermosetting matrix and the reinforcement fibers [30, 31].

The objective of this work is the development of novel, highly lightweight sandwich structures, using basalt and flax fibers as reinforcement fibers. As a core material, a polyester non-woven with hexagonal cells has been used to assess the potential of manufacturing high-performance composite sandwich panels by using a conventional vacuum assisted resin infusion moulding (VARIM) using the core as infusion media. The obtained sandwich panels have been characterized in flexural and impact conditions to understand the strength properties and the effect of silane treatment. FESEM has been carried out to analyze the interface interaction between the reinforcement fibers and the partially bio-based epoxy resin.

2. Experimental

2.1. Materials

A partially bio-based (31% renewable content according to with ASTM D6866-12) commercial-grade epoxy resin was used as the thermosetting matrix. This consisted on a base epoxy resin Resoltech® 1070 ECO and an amine-based hardener grade Resoltech® 1074 ECO from Castro Composites (Pontevedra, Spain). The resin to hardener ratio was 100/35 parts by weight as recommended by the manufacturer. The system was deeply mixed by manual methods until a uniform mix was obtained.

Two different reinforcement fabrics were used. Basalt fabric BAS 940.1270 from Basaltex® (Wevelgem, Belgium) made of 100% continuous basalt filaments. This fabric shows a specific surface weight of 940 g/cm^2 and a thickness of 0.54 mm. Flax fabrics Biotex® Flax were obtained from Composites evolution (Chesterfield, United Kingdom) with a specific surface weight of 400 g/cm^2 with a thickness of 0.7 mm.

The core material was a nonwoven Lantor Soric® XF supplied by LANTOR® (Veenendaal, The Netherlands) with a specific surface weight of 250 g/cm^2. This was used as core material and infusion media. To improve the interface interaction between the selected fibers/fabrics and the epoxy matrix, a glycidyl-functional silane (3-glycidyloxypropyl) trimethoxysilane was used as a coupling agent. This was supplied by Sigma- Aldrich (Madrid, Spain).

2.1.1. Pre-treatment of fabrics

Generally, basalt fibers are coated by a silane-based sizing to impart strands that can interfere with the panels production process. To remove it and any external impurities, basalt fibers were initially subjected to a thermal treatment at 300 ºC for 3 h.

The interface interaction between the fabrics and the matrix was enhanced by a silanization treatment. Both basalt and flax fibers were immersed in an aqueous solution with 1 wt% silane for 2 h at room temperature; then the solution was stirred with a magnetic stirrer to obtain a uniform solution. During this stage, hydrolysis of silane occurs and the subsequent hudroxyl groups move to the surface of the fabrics.

To complete the silanization process of chemical anchoring of the silanes through condensation with the hydroxyls on the surface of both fibers, an air circulating oven was used to dry the functionalized fabrics for 12 h at 80 ºC. This stage provides strong links between the hydrolyzed silane groups and the hydroxyl goupd in both basalt and flax fabrics, through a condensation process with the release of water that is removed by evaporation.

2.1.2. Manufacturing of hybrid basalt/flax composite laminates

The process used to manufacture the hybrid sandwich laminates was the vacuum assisted resin infusion moulding (VARIM), instead of using the usual process with bleeding fabric, absorption mesh, and so on, which are not the best selection to manufacture composite sandwich panels.

Sandwich panels were obtained with Soric® core that acted as porous media for infusion. As in other infusion methods, the vacuum is responsible for spreading the resin throughout the geometry of the composite sandwich and avoids agglomeration of resin in fabrics.

Different stacking sequences were manufactured, as can be seen in Table 1. The procedure was the following. First, a flat surface was cleaned beforehand, then coated by a thin layer of a release agent, poly(vinyl alcohol) - PVA. Second, a peel-ply sheet was placed on the PVA thin layer to make more accessible the unmolding process. Then the fabrics and the core were stacked as indicated in Table 1 and Figure 1a). From this step, the process is slightly different from a conventional resin infusion (VARIM). As can be seen in Figure 1b), the bleeding mesh instead of covering the whole stacking, it is only placed on one side where the resin inlet will be placed. This is responsible for ensuring the flow of the resin from the resin inlet to the core. The resin distribution tube was placed over the mesh meanwhile, the vacuum tube was coated with a felt sheet that allowed the vacuum but restricted the resin flow. Finally, all the elements were sealed with a plastic bag and a double side sealing tape (Figure 1c). To ensure no leaking resin, the vacuum was tested beforehand. Then, the resin was allowed to flow until all the sheets were completely soaked. After this, the resin supply was cut off, but the vacuum was maintained for 8 h until the resin was completely cured at room temperature. With these curing conditions, no additional post-curing process is needed. As can be seen in Figure 1d) the core helps the resin to flow through the sandwich panel. Flax fibers, due to their porous structure, were the ones that better absorb the resin, followed by the basalt fiber. The Soric® Lantor core helps the resin to be spread homogeneously through the face sheets, thus leading to a complete wetting of the composite panel.

The obtained panels were machined by a computer numerical control milling machine to obtain specimens following international standards guidelines

Table 1. Composition and coding of basalt/flax/sandwich composite panels

Code	Ply number ratio (basalt/flax)	Sandwich upper face	Core	Sandwich bottom base	Volume fraction resin/material
BBSBB	4/0	basalt – basalt	Soric® XF	basalt – basalt	52.20/47.80
BLSLB	2-feb	basalt – flax	Soric® XF	flax – basalt	62.62/37.38
LBSBL	2-feb	flax – basalt	Soric® XF	basalt – flax	63.10/36.90
LLSLL	0/4	flax – flax	Soric® XF	flax – flax	74.76/25.24
BSB	2/0	basalt	Soric® XF	basalt	58.86/41.14
LSL	0/2	flax	Soric® XF	flax	77.64/22.36

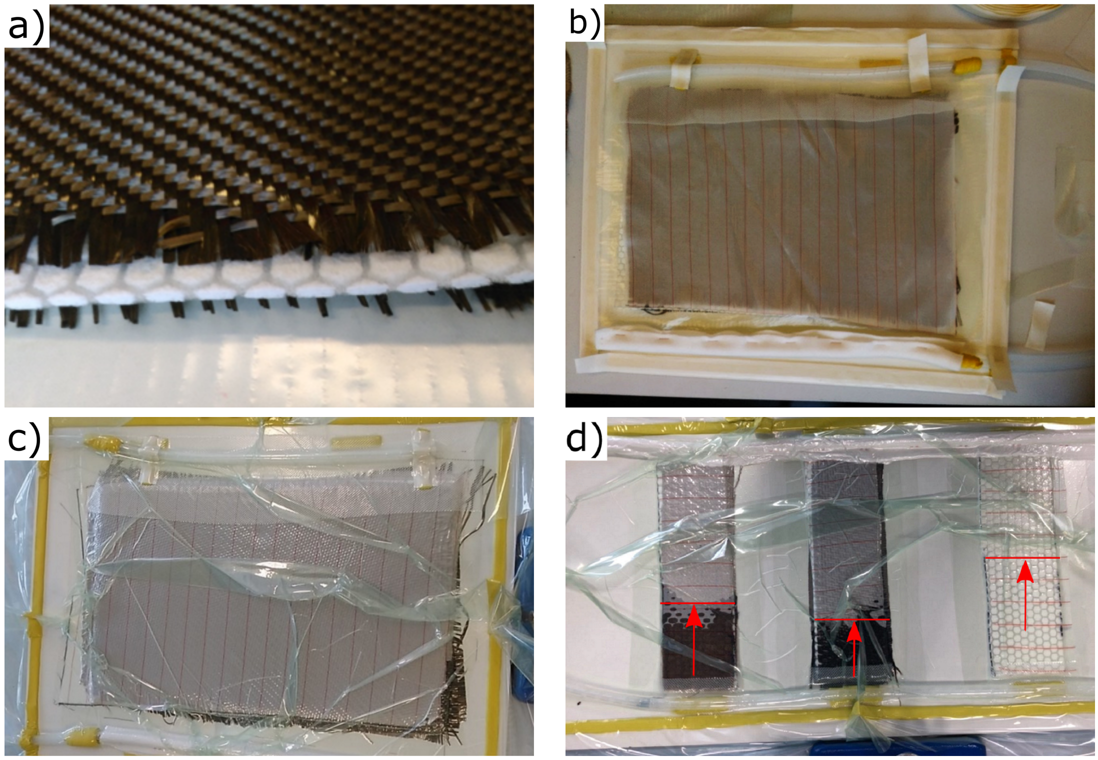

Figure 1. Scheme of the manufacturing process of basalt/flax/sandwich composites by vacuum-assisted resin infusion moulding (VARIM) with the nonwoven core as infusion media. a) stacking configuration, b) placement of resin inlet and outlet tubes, c) sealing process and vacuum test procedure, d) resin infusion process with different stacking sequences.

2.2. Mechanical properties

The mechanical properties of sandwich panels were determined in flexural and impact conditions. Flexural tests were carried out on a universal testing machine ELIB 30 form S.A. E. Ibertest (Madrid, Spain). The flexural test was performed following the ISO 14125:1998 standard. In this test, the specimen is supported on two points separated from each other, and the increasing load applied in the center with a crosshead rate of 1 mm/min. The machine was equipped with a cell load of 5 kN.

To evaluate the impact strength of the sandwich panels the Charpy test was carried out in a Charpy pendulum supplied by Metrotec (San Sebastián, Spain), using a 6-J pendulum on “U” type notched samples (radius of 0.5 mm and 2 mm depth) following the guidelines of ISO 179 standard. At least five samples of every material were tested at room temperature; the results of all tests were collected and averaged. In addition, the standard deviation was obtained to estimate the error.

2.3. Interface interaction analysis by field emission scanning electron microscopy (FESEM)

To evaluate the interface interaction between the reinforcing fibers and the epoxy matrix, samples were cryofractured and then, observed by field emission scanning electron microscopy (FESEM), in a ZEISS ULTRA 55 FESEM microscope supplied by Oxford Instruments (Abingdon, United Kingdom) working at an acceleration voltage of 2 kV. To provide electrical conducting properties to the sandwich panels, they were precoated with a gold-palladium layer using a high vacuum sputter coater EM MED20 supplied by Leica Microsystem (Milton Keynes, United Kingdom).

3. Results and discussion

3.1. Mechanical properties of sandwich panels based on basalt and flax fibers

Subjecting basalt/flax sandwich panels to flexural and impact conditions (Charpy test) gives interesting data about resistant properties as well as the ability to absorb energy in impact conditions. Figure 2 shows the values obtained from the two described tests. In sandwich materials, the core does not provide any mechanical strength to the material (in tensile conditions), so final properties are strictly based on the reinforcing fibers. Nevertheless, core materials contribute to support out-of-plane stresses by shear with the face sheets.

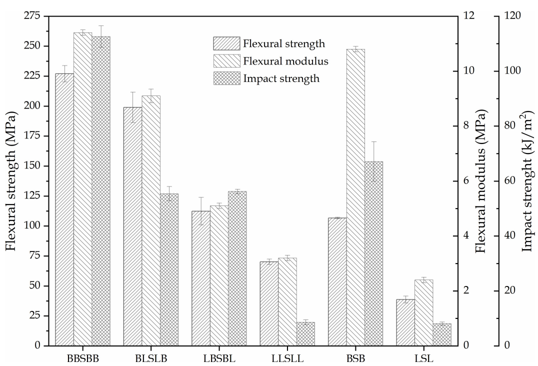

Figure 2. Mechanical properties of basalt/flax sandwich hybrid composite with different stacking sequences obtained from flexural and impact tests.

As expected, the BBSBB material with the highest number of basalt plies in its structure (4 basalt sheets, two at the top of the core and two at the bottom), shows a flexural strength, σ_f, and flexural modulus, Ef of 227±6.79 MPa and 11.35±0.037 GPa, respectively. These values as similar to other glass-fiber composite materials. The obtained values are relatively high, which means that besides the fact that basalt fibers have high resistance, the interaction of these fibers and the epoxy matrix is quite good, allowing excellent load transfer between the matrix to the fibers. These results are in accordance with the literature about basalt/epoxy systems [32].

Analyzing materials such as BLSLB and LBSBL, which have the same number of basalt and flax fibers in the face sheets (one basalt ply and one flax ply on each face sheet), but with different stacking configuration, gives impressive results. The panel with the basalt sheets in the outer side of the face sheets offers higher values of flexural strength and modulus being only 12% and 19% less, respectively, compared with the material with four basalt plies. BLSLB stacking sequence leads to interesting mechanical properties of 199±12.7 MPa and 9.14±0.25 GPa for the flexural strength and modulus, respectively.

Concerning the LBSBL material, it is worthy to remark a notorious decrease in its flexural properties both in strength and stiffness, having a decrease of 43% and 44% in the flexural strength and the flexural modulus, respectively, compared with the BBSBB composite panel. This is clearly due to the nature of the fibers that are supporting the tensile and compression stresses. In the LBSBL composite panel, flax fibers are located at the outer face. As flax fibers are less resistant than basalt fibers, the result is a noticeable decrease in its properties. Similar results were obtained by Dhakal *et al.* [33] in hybrid reinforced composites based on basalt/hemp fibers, the presence of basalt fibers in the outside of the face sheets improved the flexural strength and modulus. As expected, panels composed entirely by flax fibers are those with the more inferior flexural properties.

Figure 3 shows an example of the type of failure suffered by the panels. Figure 3a) shows the BSB material that is composed only of a basalt ply in each of the faces, as mentioned before the core used, does not provide any extra strength to the final material. It can be seen that the failure of the material is caused by the core and not by the reinforcing fibers. On the other hand, the failure of the LSL material in figure 3b) indicates this failure is due to the low resistance that the flax fibers in the bottom face sheet, which are working in tensile conditions.

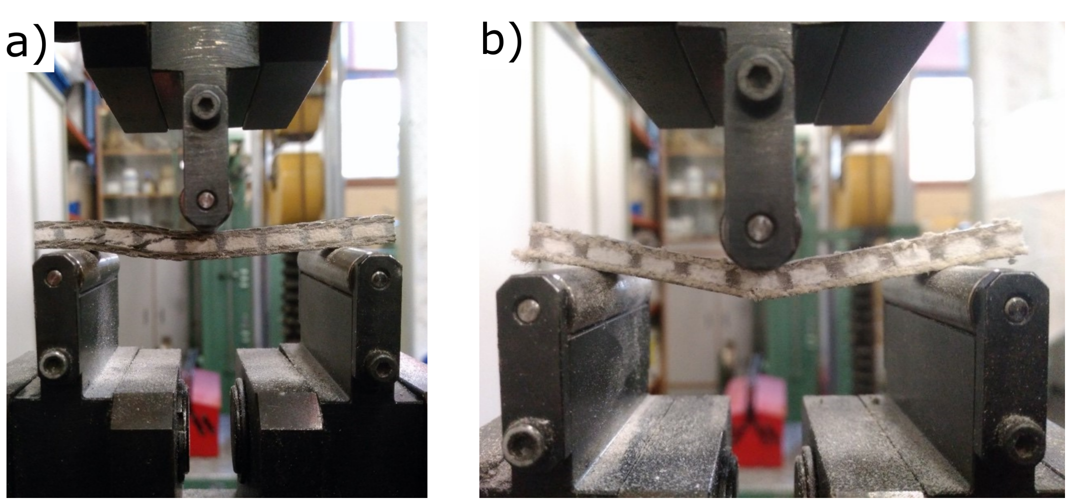

Figure 3. Forms of failure in flexion tests of a) BSB sandwich panel and b) LSL sandwich panel.

By using the Charpy impact test, one can estimate the energy that such materials can withstand under impact conditions, thus giving an estimation of the toughness.

As expected just as it happened in flexural characterization, the material composed entirely of basalt fibers (and a Soric® Lantor core), i.e. BBSBB is the one that absorbs the highest energy, obtaining values of 112.6±3.9 kJ/m^2, which is indicating good stress transfer between the matrix to the reinforcing fabrics.

Basalt fibers, due to their composition, provide high stiffness to the composite but, in contrast, basalt composites cannot support large deformations [34]. By analyzing the composite panels with the same number of basalt and flax fibers (BLSLB and LBSBL), it can be seen that the distribution of the fibers does not affect the impact energy (see Figure 2), with absorbed-energy values of 55 – 56 kJ/m^2, that are in accordance with the results reported by Fiore *et al.* [35]. They observed very slight changes in the impact strength by placing basalt or flax fibers in the outer face sheet.

As expected, just by replacing one-ply from basalt to flax, it leads to a decrease in the impact strength of about 50%. This is consistent because if one observes the BSB material made up by only one basalt layer in the face sheets, it has higher impact strength than materials that have flax fiber in their stacking sequence. It can be concluded that the impact stress is absorbed almost entirely by basalt fibers, since analyzing materials that are made entirely of flax fibers, either by four layers (LLSLL) or two layers (LSL) they have very low values and practically the same, around 8 kJ/m^2. As mentioned above, the core does not improve the final properties of composite materials.

3.2. Matrix/reinforcement fiber interface interaction

The final properties of the hybrid composite materials are related by the strength of the fibers; therefore, a good synergy between them and the matrix is necessary since a functional interaction between the fibers and the matrix will result in superior mechanical properties. This is because good fiber-matrix interactions allow stresses transfer from the matrix (with no reinforcing properties) to the reinforcing fiber [36]. So, a poor synergy between these components would result in composite materials with low mechanical properties.

For an accurate analysis of the interaction between the reinforcement fibers and the surrounding matrix, cryofractured surfaces from the face sheets were observed by FESEM (see Figure 4). Figure 4a) shows the interaction of the basalt fibers after the coupling agent treatment based on silane and the surrounding matrix. As can be seen, there is a lack of the gap between the fiber and the surrounding resin, therefore indicating that the silane treatment was successful. Similar findings were reported by Gao *et al.* [37], in silica-based fibers (glass fiber) and an epoxy matrix. They show the effectiveness of a silanization treatment on fibers which is directly related to improved mechanical properties. Figure 4b) shows the flax fibers after being subjected to the same chemical treatment with the silane coupling agent. In this case, it is shown that the interaction of the fibers was improved since the gap is very small. This improvement has also been reported by Sepe and Caputo [38], with hemp fibers subjected to a silanization process with (3-glycidyloxypropyl) trimethoxysilane as a coupling agent.

This coupling agent also decreases the hydrophilic behaviour that natural fibers intrinsically have, and this enhances the compatibility with hydrophobic polymeric matrices. Despite this, the presence of the gap does not allow a perfect stress transfer so that the final mechanical properties of panels will decline. Because the basalt fibers structure is based on silica, the effectiveness of the silanization with hydrolyzed silane, works better. The coupling agent with glycidyl-silane functionality has epoxy functional groups that can readily react with both the epoxy resin during the curing process (cross-linking) and with the hydroxyl functional groups of the basalt fibers, leading to a strong bridge between these two components.

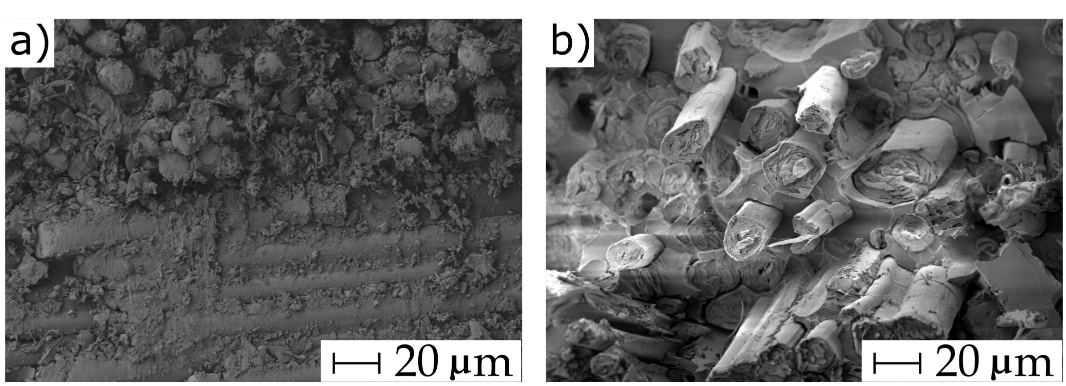

Figure 4. Field emission scanning electron microscopy (FESEM) images at ×500 magnifications corresponding to cryofracture surfaces from impact tests of a) BSB sandwich panel and b) LSL sandwich panel.

This corroborates the results obtained in the mechanical tests since the improvements of the flexural properties of the panels reinforced by basalt fibers is the result of the good synergy between these fibers and the polymeric matrix, which allows an excellent distribution of stress.

4. Conclusions

Through this research, it has been confirmed that the use of a porous core as a diffusion media in a conventional vacuum assisted resin infusion moulding (VARIM) is a successful alternative process to manufacture sandwich-type lightweight composite structures using a partially biobased epoxy resin (with 31 wt% biobased content derived from epoxidized vegetable oils). The use of an infusion core material allows reducing weight and costs of manufacturing high-tech composite parts as the typical consumable materials in a VARIM process can be reduced.

Silanes play a key role in improving mechanical performance as the provide strong links between the epxy resin (through the glycidyl functional group) and the fiber (through a condensation process of the hydrolyzed silane).

Regarding the mechanical properties of sandwich panels, the best performance is obtained in composite panels with the stacking sequence BBSBB. However, the substitution of one of the basalt fabrics in the face sheets by a flax fabric has an essential effect on overall properties, mainly on flexural strength and modulus, while impact strength remains almost invariable. Although these flax-based composite panels offer inferior properties than all-basalt composites, they represent an interesting alternative from both technical and environmental points of view.

References

[1] P. Cousin, M. Hassan, P. V. Vijay, M. Robert, and B. Benmokrane, "Chemical resistance of carbon, basalt, and glass fibers used in frp reinforcing bars," *Journal of Composite Materials*, vol. 53, no. 26–27, pp. 3651–3670, 2019. [Online]. Available: https://doi.org/10.1177/0021998319844306

[2] B. Wang, Q. Fu, H. Li, L. Qi, Q. Song, and Y. Fu, "In situ growth of graphene on carbon fabrics with enhanced mechanical and thermal properties for tribological applications of carbon fabric-phenolic composites," *Tribology Transactions*, vol. 62, no. 5, pp. 850–858, 2019. [Online]. Available: https://doi.org/10.1080/10402004.2019.1626519

[3] K. Liu, S. He, Y. Qian, Q. An, A. Stein, and C. W. Macosko, "Nanoparticles in glass fiber-reinforced polyester composites: Comparing toughening effects of modified graphene oxide and core-shell rubber," *Polymer Composites*, vol. 40, no. S2, pp. E1512–E1524, 2019. [Online]. Available: https://doi.org/10.1002/pc.25065

[4] M. S. Z. Abidin, T. Herceg, E. S. Greenhalgh, M. Shaffer, and A. Bismarck, "Enhanced fracture toughness of hierarchical carbon nanotube reinforced carbon fibre epoxy composites with engineered matrix microstructure," *Composites Science and Technology*, vol. 170, pp. 85–92, 2019. [Online]. Available: https://doi.org/10.1016/j.compscitech.2018.11.017

[5] M. Flanagan, A. Doyle, K. Doyle, M. Ward, M. Bizeul, R. Canavan, B. Weafer, C. M. Brádaigh, N. M. Harrison, and J. Goggins, "Comparative manufacture and testing of induction welded and adhesively bonded carbon fibre peek stiffened panels," *Journal of Thermoplastic Composite Materials*, vol. 32, no. 12, pp. 1622–1649, 2019. [Online]. Available: https://doi.org/10.1177/0892705718792362

[6] M. R. Ricciardi, I. Papa, V. Antonucci, V. Lopresto, and A. Langella, "Impact behavior of polyester gfrp for naval applications: Influence of the clamping device and fluid–material interaction," *Journal of Materials Engineering and Performance*, vol. 28, no. 6, pp. 3196–3202, Jun 2019. [Online]. Available: https://doi.org/10.1007/s11665-019-03902-w

[7] J. Naveen, M. Jawaid, E. S. Zainudin, M. T. H. Sultan, and R. Yahaya, "Effect of graphene nanoplatelets on the ballistic performance of hybrid kevlar/cocos nucifera sheath-reinforced epoxy composites," *Textile Research Journal*, vol. 89, no. 21-22, pp. 4349–4362, 2019. [Online]. Available: https://doi.org/10.1177/0040517519833970

[8] J. P. Arenas, J. L. C. no, L. Troncoso, and M. L. Auad, "Thermoplastic polyurethane/laponite nanocomposite for reducing impact sound in a floating floor," *Applied Acoustics*, vol. 155, pp. 401–406, 2019. [Online]. Available: https://doi.org/10.1016/j.apacoust.2019.06.012

[9] M. Zhang, O. Bareille, and M. Salvia, "Cure and damage monitoring of flax fiber-reinforced epoxy composite repairs for civil engineering structures using embedded piezo micro-patches," *Construction and Building Materials*, vol. 225, pp. 196–203, 2019. [Online]. Available: https://doi.org/10.1016/j.conbuildmat.2019.07.179

[10] M. Mudhukrishnan, P. Hariharan, K. Palanikumar, and B. Latha, "Optimization and sensitivity analysis of drilling parameters

for sustainable machining of carbon fiber-reinforced polypropylene composites," *Journal of Thermoplastic Composite Materials*, vol. 32, no. 11, pp. 1485–1508, 2019. [Online]. Available: https://doi.org/10.1177/0892705718799816

[11] R. M. Gandia, F. C. Gomes, A. A. R. Corrêa, M. C. Rodrigues, and R. F. Mendes, "Physical, mechanical and thermal behavior of adobe stabilized with glass fiber reinforced polymer waste," *Construction and Building Materials*, vol. 222, pp. 168–182, 2019. [Online]. Available: https://doi.org/10.1016/j.conbuildmat.2019.06.107

[12] A.-S. Mora, R. Tayouo, B. Boutevin, G. David, and S. Caillol, "Synthesis of biobased reactive hydroxyl amines by amination reaction of cardanol-based epoxy monomers," *European Polymer Journal*, vol. 118, pp. 429–436, 2019. [Online]. Available: https://doi.org/10.1016/j.eurpolymj.2019.06.020

[13] C. François, S. Pourchet, G. Boni, S. Rautiainen, J. Samec, L. Fournier, C. Robert, C. M. Thomas, S. Fontaine, Y. Gaillard, V. Placet, and L. Plasseraud, "Design and synthesis of biobased epoxy thermosets from biorenewable resources," *Comptes Rendus Chimie*, vol. 20, no. 11, pp. 1006–1016, 2017. [Online]. Available: https://doi.org/10.1016/j.crci.2017.10.005

[14] S. Torron, S. Semlitsch, M. Martinelle, and M. Johansson, "Biocatalytic synthesis of epoxy resins from fatty acids as a versatile route for the formation of polymer thermosets with tunable properties," *Biomacromolecules*, vol. 17, no. 12, pp. 4003–4010, 2016, pMID: 27809488. [Online]. Available: https://doi.org/10.1021/acs.biomac.6b01383

[15] M. Jebrane, S. Cai, C. Sandström, and N. Terziev, "The reactivity of linseed and soybean oil with different epoxidation degree towards vinyl acetate and impact of the resulting copolymer on the wood durability," 2017. [Online]. Available: https://doi.org/10.3144/expresspolymlett.2017.37

[16] R. Singh, B. Singh, and H. Tarannum, "Mechanical properties of jute fiber-reinforced up/pu hybrid network composites," *Polymers and Polymer Composites*, vol. 27, no. 9, pp. 546–556, 2019. [Online]. Available: https://doi.org/10.1177/0967391119852882

[17] E. Mahdi, D. Ochoa, A. Vaziri, and E. Eltai, "Energy absorption capability of date palm leaf fiber reinforced epoxy composites rectangular tubes," *Composite Structures*, vol. 224, p. 111004, 2019. [Online]. Available: https://doi.org/10.1016/j.compstruct.2019.111004

[18] A. K. Barouni and H. N. Dhakal, "Damage investigation and assessment due to low-velocity impact on flax/glass hybrid composite plates," *Composite Structures*, vol. 226, p. 111224, 2019. [Online]. Available: https://doi.org/10.1016/j.compstruct.2019.111224

[19] K. Mazur, S. Kuciel, and K. Salasinska, "Mechanical, fire, and smoke behaviour of hybrid composites based on polyamide 6 with basalt/carbon fibres," *Journal of Composite Materials*, vol. 53, no. 28-30, pp. 3979–3991, 2019. [Online]. Available: https://doi.org/10.1177/0021998319853015

[20] J. R. Vinson, "Sandwich structures: Past, present, and future," in *Sandwich Structures 7: Advancing with Sandwich Structures and Materials.* Springer Netherlands, 2005, pp. 3–12. [Online]. Available: https://doi.org/10.1007/1-4020-3848-8_1

[21] A. S. Herrmann, P. C. Zahlen, and I. Zuardy, "Sandwich structures technology in commercial aviation," in *Sandwich Structures 7: Advancing with Sandwich Structures and Materials*, O. Thomsen, E. Bozhevolnaya, and A. Lyckegaard, Eds. Dordrecht: Springer Netherlands, 2005, pp. 13–26. [Online]. Available: https://doi.org/10.1007/1-4020-3848-8_2

[22] A. Atiqah, M. T. Mastura, B. A. Ahmed Ali, M. Jawaid, and S. M. Sapuan, "A review on polyurethane and its polymer composites," *Current Organic Synthesis*, vol. 14, pp. 233–248, 2017. [Online]. Available: https://doi.org/10.2174/1570179413666160831124749

[23] M. Yaqoob, "Fabrication and structural equivalency analysis of cfrp nomex core sandwiched panels for fsae race car," *The UNSW Canberra at ADFA Journal of undergraduate engineering research*, vol. 12, no. 2, 2017. [Online]. Available: https://bit.ly/2LGQHUy

[24] C. Atas and C. Sevim, "On the impact response of sandwich composites with cores of balsa wood and pvc foam," *Composite Structures*, vol. 93, no. 1, pp. 40–48, 2010. [Online]. Available: https://doi.org/10.1016/j.compstruct.2010.06.018

[25] G. Zhang, B. Wang, L. Ma, L. Wu, S. Pan, and J. Yang, "Energy absorption and low velocity impact response of polyurethane foam filled pyramidal lattice core sandwich panels," *Composite Structures*, vol. 108, pp. 304–310, 2014. [Online]. Available: https://doi.org/10.1016/j.compstruct.2013.09.040X

[26] L. He, Y.-S. Cheng, and J. Liu, "Precise bending stress analysis of corrugated-core, honeycomb-core and x-core sandwich panels,"

Composite Structures, vol. 94, no. 5, pp. 1656–1668, 2012. [Online]. Available: https://doi.org/10.1016/j.compstruct.2011.12.033

[27] R. Stewart. (2011) Sandwich composites excel at cost-effective, lightweight structures. [Online]. Available: https://bit.ly/2YAF3Q5

[28] R. Chatys, A. Panich, R. S. Jurecki, and M. Kleinhofs, "Composite materials having a layer structure of "sandwich" construction as above used in car safety bumpers," in *2018 XI International Science-Technical Conference Automotive Safety*, April 2018, pp. 1–8. [Online]. Available: https://doi.org/10.1109/AUTOSAFE.2018.8373320

[29] S. H. Eum, Y. H. Kim, J. W. Han, K. J. Kim, D. H. Shin, C. Yim, and R. Murakami, "A study on the mechanical properties of the honeycomb sandwich composites made by vartm," in *Advances in Fracture and Strength*, ser. Key Engineering Materials, vol. 297. Trans Tech Publications Ltd, 8 2005, pp. 2746–2751. [Online]. Available: https://doi.org/10.4028/www.scientific.net/KEM.297-300.2746

[30] J. M. España, M. D. Samper, E. Fages, L. Sánchez-Nácher, and R. Balart, "Investigation of the effect of different silane coupling agents on mechanical performance of basalt fiber composite laminates with biobased epoxy matrices," *Polymer Composites*, vol. 34, no. 3, pp. 376–381, 2013. [Online]. Available: https://doi.org/10.1002/pc.22421

[31] M. D. Samper, R. Petrucci, L. Sánchez-Nacher, R. Balart, and J. M. Kenny, "New environmentally friendly composite laminates with epoxidized linseed oil (elo) and slate fiber fabrics," *Composites Part B: Engineering*, vol. 71, pp. 203–209, 2015. [Online]. Available: https://doi.org/10.1016/j.compositesb.2014.11.034

[32] R. Petrucci, C. Santulli, D. Puglia, F. Sarasini, L. Torre, and J. M. Kenny, "Mechanical characterisation of hybrid composite laminates based on basalt fibres in combination with flax, hemp and glass fibres manufactured by vacuum infusion," *Materials & Design*, vol. 49, pp. 728–735, 2013. [Online]. Available: https://doi.org/10.1016/j.matdes.2013.02.014

[33] H. N. Dhakal, F. Sarasini, C. Santulli, J. Tirilló, Z. Zhang, and V. Arumugam, "Effect of basalt fibre hybridisation on post-impact mechanical behaviour of hemp fibre reinforced composites," *Composites Part A: Applied Science and Manufacturing*, vol. 75, pp. 54–67, 2015. [Online]. Available: https://doi.org/10.1016/j.compositesa.2015.04.020

[34] S. Boccardi, N. D. Boffa, G. M. Carlomagno, G. D. Core, C. Meola, P. Russo, and G. Simeoli, "Inline monitoring of basalt-based composites under impact tests," *Composite Structures*, vol. 210, pp. 152–158, 2019. [Online]. Available: https://doi.org/10.1016/j.compstruct.2018.11.038

[35] V. Fiore, T. Scalici, L. Calabrese, A. Valenza, and E. Proverbio, "Effect of external basalt layers on durability behaviour of flax reinforced composites," *Composites Part B: Engineering*, vol. 84, pp. 258–265, 2016. [Online]. Available: https://doi.org/10.1016/j.compositesb.2015.08.087

[36] D. Lascano, L. Quiles-Carrillo, S. Torres-Giner, T. Boronat, and N. Montanes, "Optimization of the curing and post-curing conditions for the manufacturing of partially bio-based epoxy resins with improved toughness," *Polymers*, vol. 11, no. 8, 2019. [Online]. Available: https://doi.org/10.3390/polym11081354

[37] X. Gao, R. E. Jensen, W. Li, J. Deitzel, S. H. McKnight, and J. R. J.W. Gillespie, "Effect of fiber surface texture created from silane blends on the strength and energy absorption of the glass fiber/epoxy interphase," *Journal of Composite Materials*, vol. 42, no. 5, pp. 513–534, 2008. [Online]. Available: https://doi.org/10.1177/0021998307086203

[38] P. K. Kushwaha and R. Kumar, "Effect of silanes on mechanical properties of bamboo fiber-epoxy composites," *Journal of Reinforced Plastics and Composites*, vol. 29, no. 5, pp. 718–724, 2010. [Online]. Available: https://doi.org/10.1177/0731684408100691