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Original Article

Impact behavior of laminated composites built with fique fibers and epoxy resin: a mechanical analysis using impact and flexural behavior

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ABSTRACT

This research analyzes the behavior of natural fiber reinforced laminated polymer composites (NFRPC) under mechanical solicitations. Samples were fabricated with epoxy resin matrix reinforced with a multilayer natural fique fiber in a bi-directional commercial fabric configuration. Different reinforcement contents without additives were prepared taking in the account the simplicity in processing, fabrication cost, and applications in which this material might be used with high performance standards. Charpy notched impact and 3-point bending test were carried out to evaluate the mechanical behavior and the work of fracture, which was improved significatively with the fibers, showing an increase from 5 to 30 kJ/m^2, a very significant improvement for ballistic applications. These results are compared with the Split-Hopkinson pressure bar tests conducted in previous analysis (SHPB) for the same material. The microstructure was investigated using scanning electron microscopy. Results reveal the formulation support this material as a high-performance solution for impact applications and it is suitable for substitute traditional expensive materials.

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1. Introduction

Over the last fifty years the plastic manufacturing sector has growth exponentially, particularly due to the use of composites with synthetic fillers or fibers known as *FRPs* (Fiber Reinforced Plastics). These materials have a significant impact in a lot of engineering sectors, with applications including aerospace, automobiles, and construction industry [1]. The use of synthetic fibers confers to the material greater specific properties such as

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light weight and higher strength compared with the plastic by itself. However, the main challenge in the use of those materials over the past years, does not concern to the improvement of their properties but the environmental threat that represents. FRPs with synthetic fibers are very difficult to decompose due to their components and the process to manufacture Glass fiber and Carbon fiber, as a waste, can be treated as hazardous and could be threatening the human life [2–4]. In order to solve this problem the use of plant based fibers from natural sources has been widely studied to work as a sustainable and eco-friendly replacement for the synthetic fibers [5]. In addition, an economic assessment of both, synthetic and natural fibers, probe that the differences in cost make the natural fibers a most attractive choice [6] (natural fibers: 200–1000 US/Ton, carbon fiber: 12,500 US/Ton). Currently, natural fibers can be used in both thermoset or thermoplastic matrixes, a thermoset polymers are the most popular choice due to the adhesion qualities exhibited and the wide field of applications [7–9]. Regarding the fiber selection, there are several options to be considered that depends on variables such as: The application to be used, the desired properties to achieve (weight, strength), the form of application of the fiber (chopped, uni-directional, bi-directional, woven mat, aligned, or randomly oriented), and finally, the availability of the fiber depending on the region of use [10,11]. Some of the most used natural fibers in *FRPs* are flax, hemp, coir, bamboo, bagasse, kenaf, piassava, sidal, agave, and fique [12,13].

Fique fibers are extracted from the Fique plant, also known as *Furcraea Andina*, is a native plant commonly found in regions near the mountain chain of the Andes, and due to the adaptability of this crop it was easily spread to other regions in South America, see Fig. 1. The Fique leaves are harvested in order to separate the fibers, which are refined passing through a drying process, then spun to yarn, and threaded to manufacture typically fabrics, ropes, and other handy crafts used in agriculture mainly [14,15]. Colombia particularly, is the major fique fiber producer globally, with almost 30,000 Tons per year [16]. Moreover, the potential of these fibers and fabrics exceeds the previous mentioned applications gaining importance in the field of the composite materials, showing a lot of interest using it as reinforcement for polymer composites in high-performance applications [15,17–19]. In the military industry, these composites are being used as a proposition for bullet proof panels [20–22], parts involving high impact requirements [18,23], fillers in building and structural materials [24–27], in composites for the automotive industry with Eco-Design, and sustainable materials applications using concepts of circular economy: light weight strategies directly related to fuel economy that leads to pollution reduction [25,28–30]. Additionally, these fibers are used in non-conventional fields like arts [31,32]. Thus, this natural fiber could enable a new sustainable manufacturing race, considering its performance in specific properties, and its feasibility for diverse manufacturing techniques.

Regarding the composites manufacturing with natural fibers, there is abundant information that summarizes their advantages in impact applications. Vijayakumar et al. [33] affirm that the incorporation coconut spathe in a thermoset matrix of epoxy resin, increase the energy absorption of the material. Shalwan and Yousif [6] performed a complete research in which the mechanical and tribological behavior added by the natural fibers improve the general behavior of the matrix materials. Other authors like Muneer et al. [34] highlight the performance of the natural fibers in military applications due to the ability to absorb impacts, however, also remarks the importance of the improvement of manufacturing technologies that overcome natural fiber problems such as the moisture content and the chemical composition of the different types of plant based fibers.

Nowadays in the automotive industry, big car manufacturers replaced successfully parts of the car interior and under the hood parts such as panels and insulators for *NFCs* (Natural Fiber Composites) [35,36]. This approach to the change traditional materials in the automobile sector goes hand to hand to the need of sustainable and recyclable materials and also with the need of high performances materials with better specific properties, ergo, and light weight. This feature can lead to a reduction in the fuel consumption.

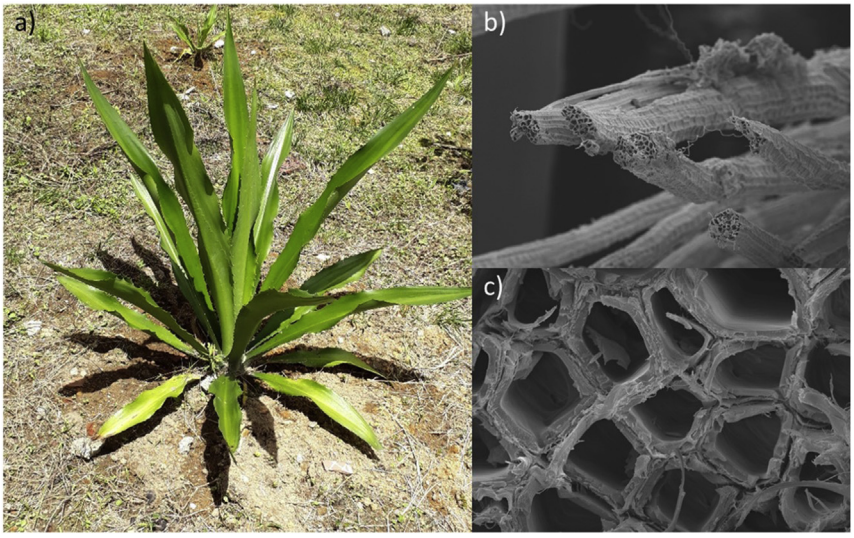

Fig. 1 – Fique plant and detail of the fiber structure using SEM.

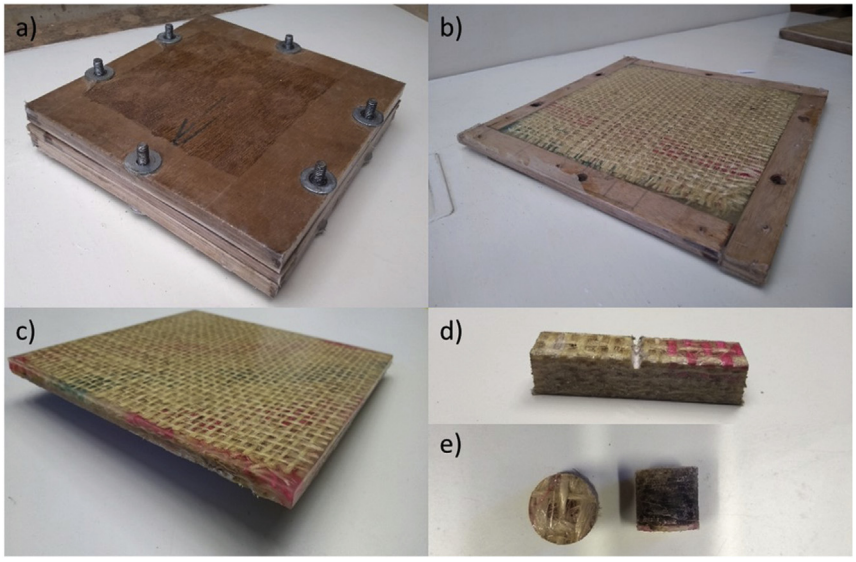

Fig. 2 – Sample manufacturing for Charpy and compression tests: a) mold, b) demolding process, c) final product, d) Charpy Impact sample, and e) SHPB samples.

In this work, the main objective is to evaluate the properties of an experimentally design laminated composite with epoxy resin matrix reinforced with a 2D trim of fique layers by mechanical characterization using Charpy impact, and flexural 3-point bending tests, both compared with Split-Hopkinson pressure bar (SHPB) tests. Furthermore, SEM (*Scanning electron microscopy*) is used to support the data.

2. Materials and methods

Wood rectangular molds were manufactured as an assembling, with a configuration that uses hexagonal screws to attach the upper cover to the body of the mold in order to squeeze the resin excess during the molding and pressure during the curing process (see Fig. 2a). The laminated composites were fabricated using a bi-component epoxy resin type A/B (A: Epoxy, B: Hardener). The main properties of the resin are described in Table 1.

A commercially trimmed fique obtained from the fique bags for coffee exports (known as sacos de cabuya) was used as a reinforcement, with a layer orientation of 0°/90° and 45°/−45° sequentially alternated up to 11 layers and 10 mm sample thickness. To fabricate the laminated composite, each layer of fabric was embedded in the already prepared and mechanically mixed resin. The porous structure of the fique fibers can incorporate large amount of resin (See Fig. 1). Thus, 250 g of epoxy resin were prepared for each batch, then, each layer was submerged into the resin until fully impregnation. Before the gel time started, each prepreg piece of fabric was placed into the mold in the layer orientation defined above until the number of

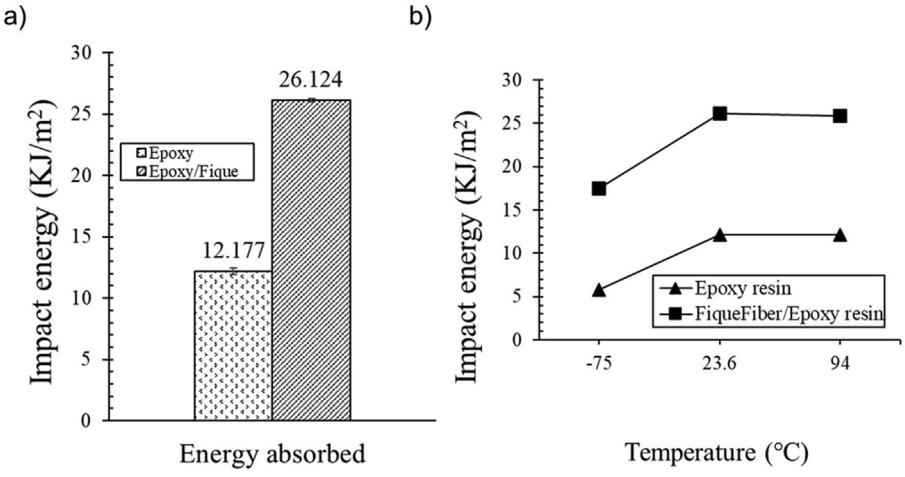

Fig. 3 – Charpy test for epoxy resin and its composite: a) room temperature results, b) results at three different temperatures.

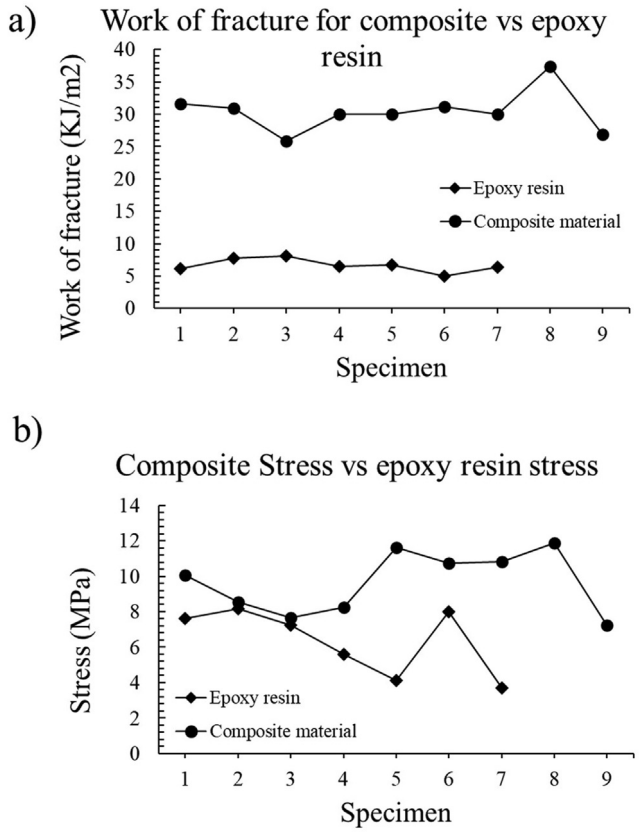

Fig. 4 – From work of fracture to stress behavior for various specimens: a) Work of fracture of epoxy resin vs epoxy/fique composite. b) Stress behavior of epoxy resin compared to the epoxy/fique composite.

layers for the composited were fulfilled. Thereafter, the mold was firmly closed (producing the draining of the resin in excess) with screws in order keep the dimensions of the sample during the curing time. The final composites had a mean composition of 220 g of epoxy resin and 150 g of fique layers. The curing process was carried out according with the supplier indications, with additional 24 h after demolding to settle.

All samples were subject to a post-process was performed to obtain samples according to geometry specifications to carry out a mechanical characterization of the material. For the Charpy notched impact test, samples were made according to the ASTM E23-00 [37] with a V type groove. For flexural test, samples were fabricated according to the ASTM D7264 for polymer composites [38]. And in order to compare those results, conventional compression of Split-Hopkinson pressure bar (SHPB) tests were carried out in epoxy resin and composite samples at Missouri S&T Labs [39,40].

For the scanning electron microscopy (SEM) examination, samples were sputtered in a Hummer 6.2 system (15 mA AC operated for 30 s) generating a thin solid film of pure gold, in order to observe the fracture modes. The SEM was a JEOL JSM 6490LV apparatus operated in high vacuum mode.

Table 1 – Resin type properties description technical data.

	Component A: Epoxy Resin	Component B: Hardener
Density at 20 °C	1.103 ± 0.02 g/ml	1.006 ± 0.02 g/ml
Viscosity at 25 °C	700–1500 mPas	200–400 mPas
Appearance	Translucid	Yellow colored
Gel time: 30–35 min – Curing time between 12 and 24 h		
Mix proportion: 24 parts of Component B per each 100 parts of Component A		

3. Results and analysys

Fig. 3 shows the significant improvement in impact behavior in terms of the energy absorption when adding fique knitted fibers as a natural reinforcement. The natural fiber enhances the capability of the material to absorb load distributed in the reinforcement. The addition of reinforcement material improves significantly values of strength, flexibility, and impact strength because of the continuity of the fabric [41–43]. Fig. 3b shows Charpy impact responses at low temperatures and high temperatures, finding the fragile material under the low temperature conditions. The composite absorbs almost an average of three times more energy than the epoxy matrix without any reinforcement, meaning that even under extreme temperatures, the reduction of stiffness of the material due to the fiber is unchanged [44,45].

The impact energy or absorbed energy known as work of fracture [46], summarized in Fig. 4, which is directly proportional to the fracture toughness. The work of fracture is described as the energy required to propagate the fracture along the analyzed material [47]. As expected, the work of fracture is high for the resin and lower for the composite material. Moreover, the flexural strength was also improved for the composite, see Fig. 4b.

Fig. 5a and b shows Scanning Electron Microscopy (SEM) images for the evaluated samples. The samples just having the neat epoxy resin revealed a more fragile behavior with a clean and continuous crack growth, which produces lower work of fracture values when compared with other composites [48].

However, in the composite, the path for the crack it is interrupted by the fiber, which forces the crack to look for another path in order to grow, and thus producing the effect of increased strength, see Fig. 5c and d. These images also clearly show that not only the impregnation of the fibers by the resin, but also the adhesion fiber-resin is good, which certainly is beneficial for the composite properties.

Three-point bending tests were carried out to analyze the flexural behavior in the composite. Fig. 6a show the setup of the samples in which the load is applied perpendicular to the fique fabric in the composite, and in Fig. 6b, the behavior of each specimen is shown in terms of the Flexural Strength and the deflection.

The presented composite material is highly suitable for applications in which the main characteristic is the impact absorption, as explained by Garcia Filho and Monteiro [49] with the premise of a low backface signature injury (BFS), the BFS probe to be acceptable with the use of different natural fibers as backing for ballistic armor in clothing [50,51]. Since one of the purposes of the fibers in the composite is the absorption of the

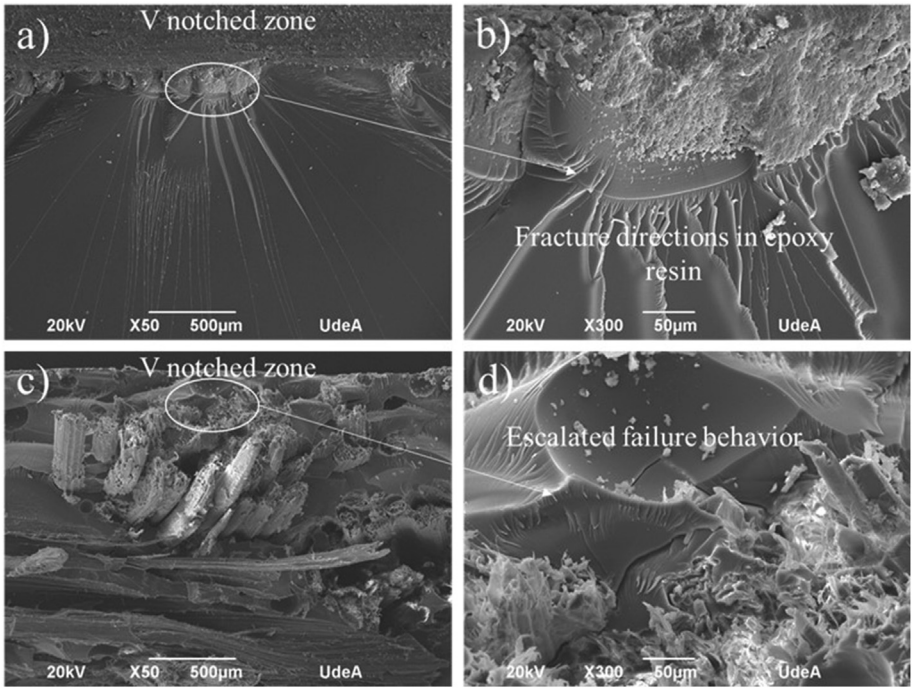

Fig. 5 – Charpy impact behavior: a) Epoxy resin at 50×. b) Epoxy resin at 300×. c) Epoxy/fique composite at 50×. d) Epoxy/fique composite at 300×.

inertia developed by projectiles, the resultant deformation, in addition with the high absorbed energy of the composite when compared with the matrix alone, highlight the use of NFRC (Natural Fiber Reinforced Composites) as a resourceful material for ballistic protection applications, see Fig. 7. Furthermore, the use of natural fibers as a reinforcement encourage a new era in military materials that have already been in other areas where laminated composites are required, such as in the automobile industry, used in panels of vehicles with lightweight characteristics and a good response to impacts [29,30,52].

Fig. 8 shows the energy absorption using the Charpy impact test compared with the instrumented impact test. The principle of both tests is the same, but the accuracy varies by using ultimate technology sensors to capture and record the variables related such as energy, maximum force, and stress by supplying the geometries of each sample. Therefore, the impact strength is more than 10% of the measured with the non-instrumented test, which again highlights the improvements of using a natural fiber reinforcement as a filler to achieve a higher energy absorption [18,53,54].

The samples of Epoxy/Resin composite were evaluated under impact and flexural conditions, the main aspects are summarized in Fig. 9. The correlation of these tests is based in the assumption of a static load applied at the center of the sample geometry and supported in two points, the difference between flexion and impact test are the velocity of the load. However, some relations can be stablished, such as the maximum force achieved during the test. This assumption is based on the differences in the distance between the two fixed points defined for the support (100 mm for 3-point bending test, 50 mm for impact test). This behavior is compared with the work of Sideridis and Papadopoulos [55] in which a short beam test is used in epoxy composites to determinate the influence of the distances between points (L) and the thickness of the sample (t), in a relation L/t, the shear properties, force, and MOE varies depending of this ratio. According with other authors, lower ratios reveal a shear failure mode, but bigger ratios experiment a flexural behavior, reaching major values of stress [56]. This case can be observed and compared with the flexural and impact behavior of the analyzed composite Epoxy/Fique, in which for impact there is a lower L/t ratio, compared with the 3-point bending test. Also, the variations, voids, irregularities in the interface can be a variable for the resultant data.

Fig. 10a shows the behavior of two specimens of composite material is analyzed and compared using SHPB and 3-bending point test. Both methods can be compared regardless the dynamic and static differences between them, and considering the reaction in the supports [57].

The SHPB test is a dynamic approach that relates the wave propagation and the geometry changes in the section area, measuring a reflected wave from the striker tool to the sample and vice versa [39,58,59]. By registering the incident and the transmitted wave, the apparatus can retrieve the signals and construct the engineering strain and after the Stress, force, displacement, and velocity can be measured [60,61].

Fig. 10b shows the SEM images for the fractured surfaces after the Flexural (3-point being test) and SHPB tests respectively, revealing a smoother surface for the SHPB sample, which could be explained as more fragile mode of fracture due to the high strain rates when compared with the flexural test.

Fig. 11 shows SEM for samples after being tested in the Split Hopkinson Pressure Bar. It is observed a large structural damage over the thickness of the sample, not homogeneous from the microstructural point of view. At the top of Fig. 11a,

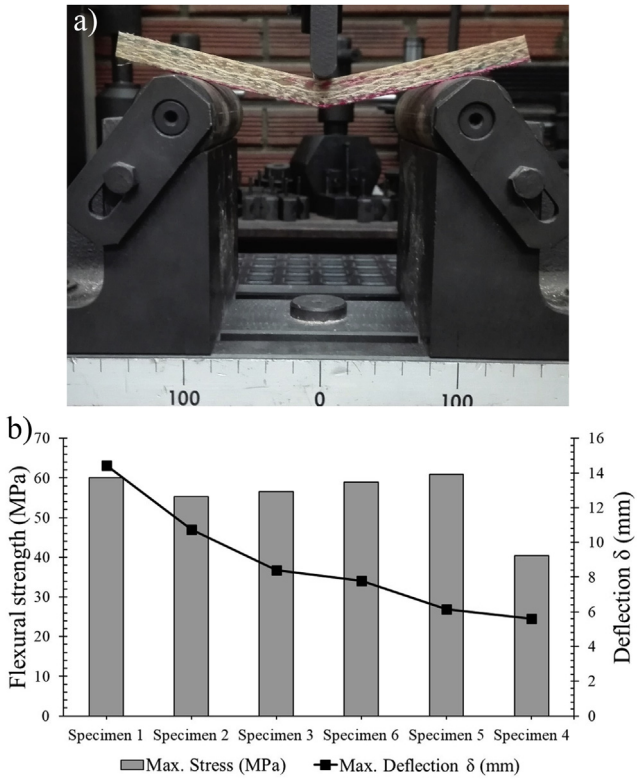

Fig. 6 – a) Flexural behavior of the composite material; b) Flexural behavior of composite specimens under centered constant load.

the sample look more compressed, while below, a large and clean fracture is developed. Fig. 11b is a magnification of a), revealing the effect of the impact loading: fique fiber detaching, which is not bad from the toughness point of view, it contributes to a better material for energy absorption. Fig. 11c shows the epoxy resin upon the loading damage, evidencing a fast and more fragile crack growth when compared with the composite material. And Fig. 11d shows details of the crack surface for the epoxy samples, with some polymer debris generated during the damage. Upon the shock loading, the fibers in the composite are stretched out absorbing large amount of

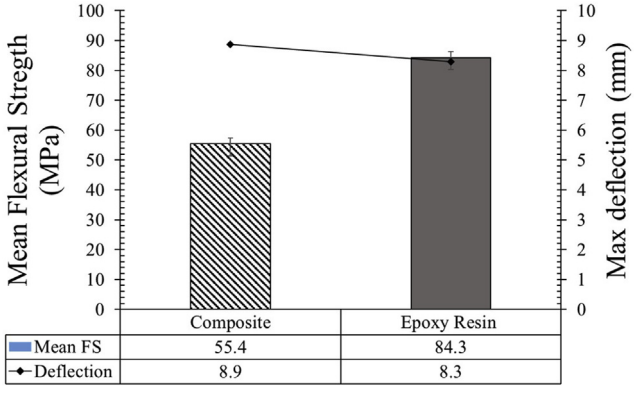

Fig. 7 – Flexural behavior of Epoxy resin compared with the composite samples.

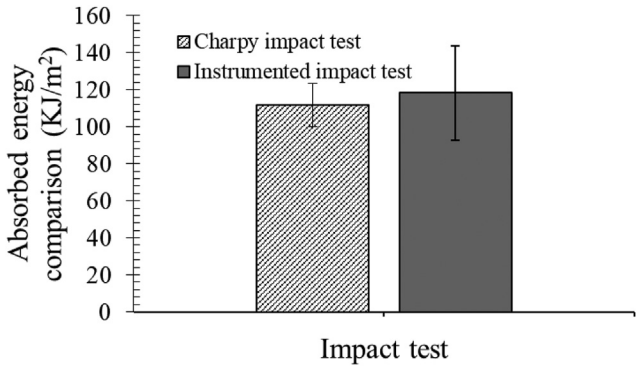

Fig. 8 – Energy absorption using Charpy impact test compared with instrumented impact test.

energy from the striker, increasing the composite tensile and impact strength, which explain the better performance referred before in the presented results, as has been described before [58].

Fig. 12 is a comparison of the microstructure of the samples upon Charpy impact and SHPB tests. Samples summited to SHPB test experiment a deformation or a wave transmission, instead of the crack propagation observed in the Charpy or in the instrumented impact tests. There is a clear region of the sample deformed similarly to the one occurred under compression

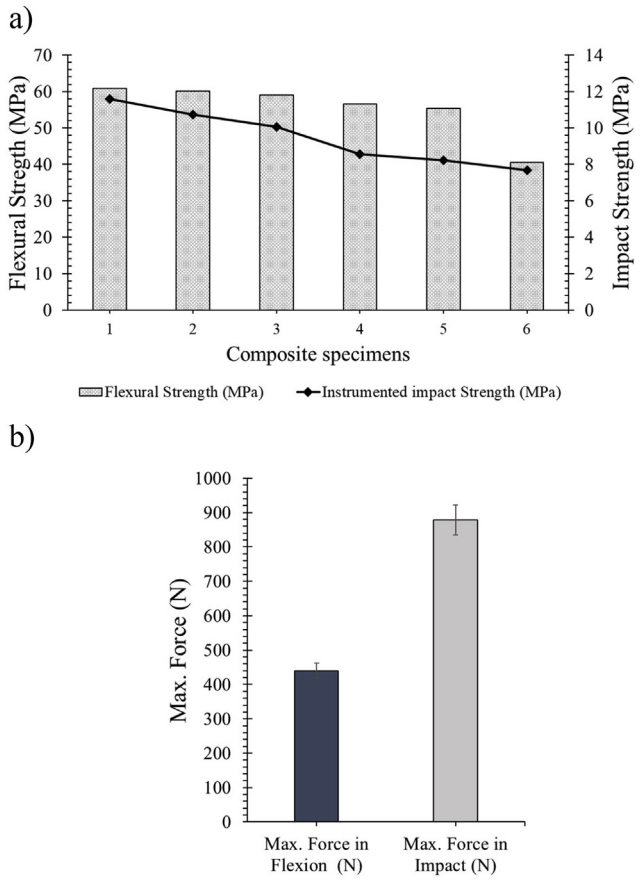

Fig. 9 – Flexural behavior compared with instrumented impact analysis: a) Mean stress (MPa), b) Max Force (N).

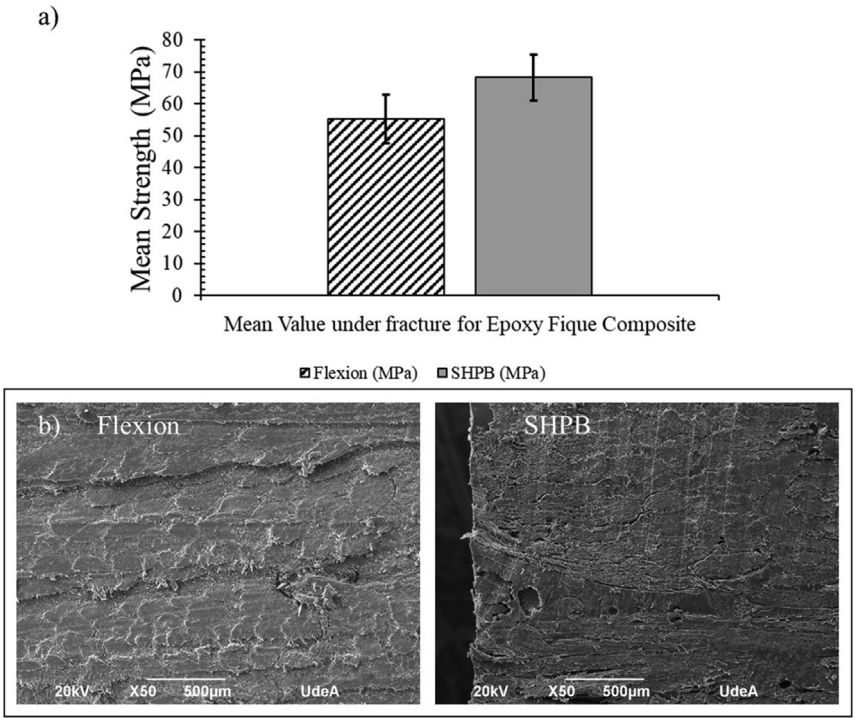

Fig. 10 – a) Mean Stress comparison for both Flexural vs SHPB tests, b) SEM for the fractured surfaces after the Flexural and SHPB tests.

loads, which can be explained as a consequence of the uneven deformation transmission through the sample thickness. The quantitative results also give support to these differences, in the case of SHPB samples, the mean value of strength in the composite material is 68.2 MPa; while in the composites analyzed under the instrumented impact test the mean value reached

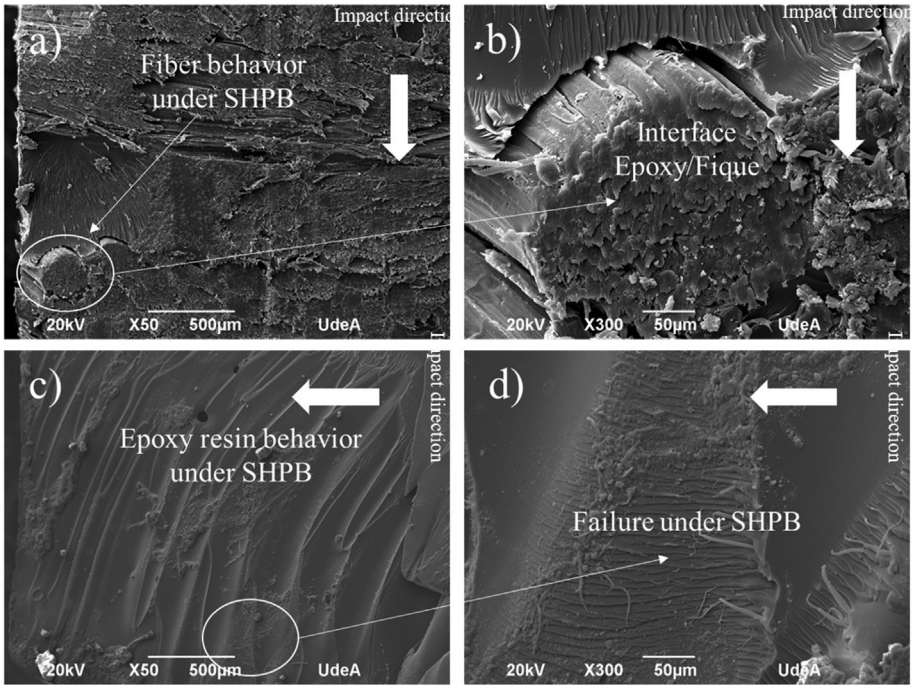

Fig. 11 – SHBT behavior of Epoxy resin and Composite Epoxy/Fique. a) Composite material under SHBT at 50×. b) Interface magnification at 300×. b) Epoxy resin behavior under SHBT at 50×. c) Magnification of failure of Epoxy resin under SHBT at 300×.

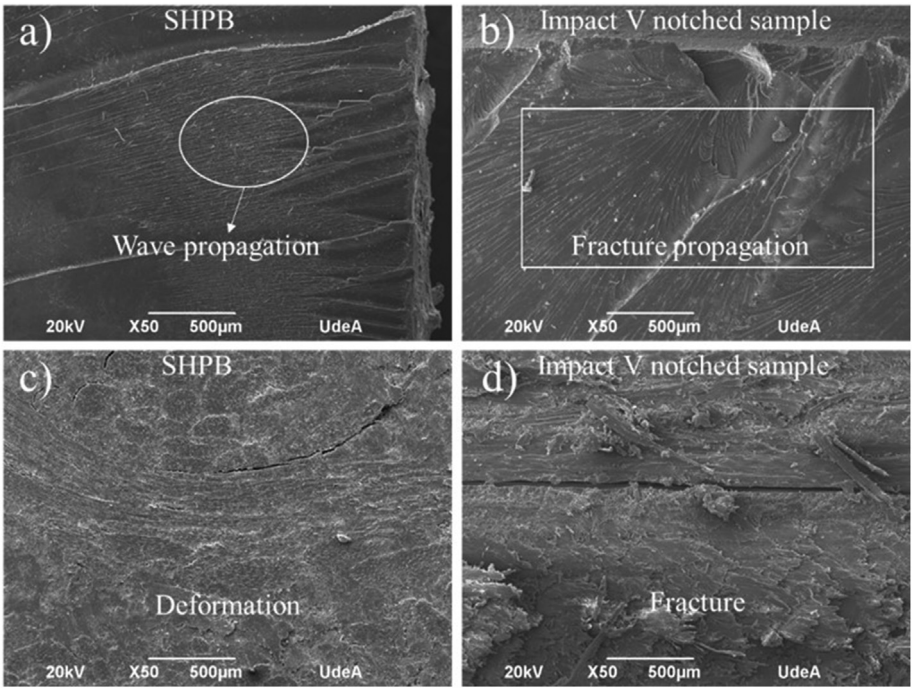

Fig. 12 – Impact vs SHPB test. a) Epoxy sample under SHPB b) Epoxy V notched sample under impact. c) Composite under SHPB test c) Composite V notched under Impact test.

9.7 MPa. In addition, the testing methods are quite different in the geometry of the samples, the striker geometry, the dynamic type load: a local direction in SHPB test against a disrupted energy guided in a V notched sample.

4. Discussion

Epoxy/Fique composites were successfully manufactured in this work aiming impact applications, by comparing flexion, instrumented Charpy, and SHPB tests. This composite can be a substitution to imports of commercial materials applied in the armor industry, particularly in developed countries, where the purchasing of traditional army materials is quite expensive and limiting for the developing of these technologies locally. At a first glance, the most potential application for these formulations are related but not limited to the military field as a antiballistic shield [62]. Natural fabric can be as resistant as the known antiballistic textile fabrics: aramid, UHMWPE (ultra-high molecular weight polyethylene), glass fibers fabrics, and carbon fiber fabrics, among others. The principle behind the NFRC is the fiber ability to transmit the impact trough the composite as any other antiballistic fabric would do it and the performance is comparable in terms of BFS [63,64]. Moreover, the natural fibers are beneficial not only because of their low carbon footprint contribution, but also because of their low weight, low costs, and

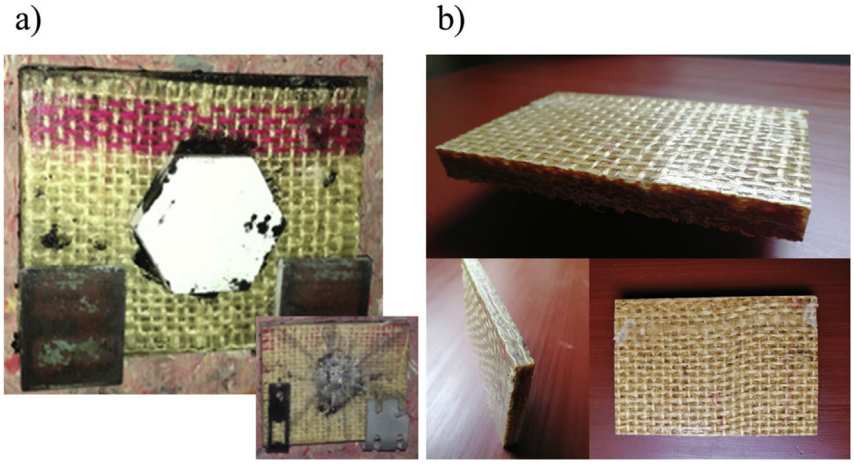

Fig. 13 – Laminated composite: a) Polyester composite reinforced with fique fiber for ballistic test (Taken and reprinted from Pereira A. C. et al. [22]). b) Epoxy/Fique composite experimental approach (Own Image).

perhaps, more importantly, for the potential of create new and innovative businesses in the countries with these materials, working for a more sustainable economy and environment [65].

Other experiments involving ballistic proves for the same fiber reinforcement but with a polyester matrix have showed amazing results, also very versatile in the manufacturing, see Fig. 13a. Unlike this research that uses polyester, the use of epoxy resin in our investigation provided a higher performance in the composite for the very own nature of the resin [66]. However, being a thermoset material represents a disadvantage in terms of processing, limited to laminating or molding, but acceptable considering the performance and application. Also, the ballistic properties of this composite can be attributed to the high impact resistance and energy absorption, phenomena is explained by other authors as the distribution of stress in the delamination and permanent indentation due to loads or dynamic charges (projectiles), and as a more damage tolerance of the resin under environmental conditions as well [67].

The performance of this kind of composite is also evaluated in the building and construction industry due to the improved properties of high strength, impact resistance, flame retardant (depending on the fillers), wear resistance, corrosion resistance, damping and acoustic properties [68,69], insulation properties, and chemical resistance, among other advantages [25]. The epoxy resin, with the higher viscosity represents an improvement in terms of UV resistance, making this material suitable for construction and outdoor applications [70] for regular or building under potential impact loadings.

This work can be extended to the automotive industry, in which is crucial the weight reduction, as the natural fibers can accomplish this feature [13,71]. In the automotive industry, the NFRC must be able to process in different methods besides molding, compression, and lamination. Thus, the used of particulate fillers can be also a way to explore. The most highlighted feature is the potential economy with the materials used nowadays like GFRC or talc fillers for PP and P/E with impact requirements for automotive parts [72]. Other composites tested on this field with kenaf fiber as a filler show a high profitability with a range of saving from 2 to 2.5 USD/kg with a base price for E glass fiber between 3 and 3.25 USD/kg [73]. The present analysis encourages the use of NFRC, in this case Epoxy/fique laminated composites as a suitable option for a wide range of applications.

5. Conclusion

In this research, fique fibers were used as reinforcement of an epoxy resin material Charpy impact, 3-point bending test were carried out. The comparison with Split-Hopkinson pressure bar (SHPB) revealed new limits of these materials by analyzing the dynamic behavior of the specimens. It was found that the fabricated composite material has a lower rigidity when compared to the epoxy resin, and showed a better behavior under stress conditions as well, in addition to a non-brittle failure mode, and to a more flexible behavior. Both, SHPB test and instrumented or Charpy impact test probe the behavior of the composite material compared to the epoxy resin by itself, revealing a better behavior regarding the strain under dynamic load and a better behavior of the impact under static load. In order to expand the results of the present research, a more exhaustive parameter optimization of the layer configuration is recommended. In Colombia, the Fique fibers and textiles are a very known industry, and the production of this material is around 30 KTons/year. Those materials result in a very attractive source for new developments, in this case NFRPC, the applicability and the potential for composites fabricated with this type of reinforcement relies on the economy of the country, with particular applications in the automobile industry in which the reliability, weight reduction, cost reduction and material sources are critical points or evaluation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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