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Implementation of eco-sustainable biocomposite materials reinforced by optimized agave fibers

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Abstract

Although several works have recently been published in literature about biocomposites, i.e. about composites with polymeric matrix reinforced by natural fibers, only a few articles have been devoted to the implementation of high performance biocomposites for structural and semi-structural applications. The present study aims to give a contribution by considering biocomposites obtained by using an eco-friendly partially bio-based epoxy (green epoxy) and sisal (agave sisalana fibers) obtained by a proper optimization process.

Through a systematic experimental analysis, three different types of biocomposites obtained with a suitable manufacturing process, such as random short fiber biocomposites, random discontinuous fibers biocomposite obtained through the preliminary manufacture of MAT fabrics, and unidirectional long fibers biocomposites obtained through the preliminary manufacture of unidirectional "stitched" fabrics, have been studied.

Keywords: biocomposites; natural fibers; agave fibers; eco-friendly matrices.

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1. Introduction

Biocomposites reinforced with agave fibers are eco-compatible or renewable materials already used in the automotive field and in other field of the industrial production, limited to non-structural applications (filling

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material, soundproofing, etc.), in which the particular properties, such as lightness and low cost, both lower than those of any composite reinforced with synthetic fibers, along with good thermal and acoustic insulation capacity, are particularly appreciated.

Such biocomposites for non-structural applications are generally constituted by environmentally friendly polymer matrix composites reinforced with short or discontinuous agave fibers, randomly oriented; commonly, they are obtained by molding or extrusion processes, and are characterized by low mechanical strength, usually comparable with that of the matrix, along with higher stiffness properties.

Although agave fibers have good mechanical characteristics, combined with high toughness, good fiber-matrix adhesion and low damageability, characteristics that can also be further improved with a suitable optimization procedure (proper selection and suitable extraction process, see Zuccarello and Zingales (2017), Zuccarello and Scaffaro (2017)), at present high performance eco-sustainable or renewable bio-composites that could be used in structural and semi-structural applications (see Murherjee and Satyananrayana (1987), Belaadi et al. (2014), Chand and Hashimi (1993), Chan et al. (1989), Silva et al. (2008), Thomason et al. (2008), Belaadi et al. (2008), Kaewkuk et al. (2013), Bisanda and Ansell (1999), Joseph et al. (1996), Singh et al. (1996)), have not yet been fully developed. The need for high performance renewable biomaterials is particularly felt in the automotive field (Furqan et al. (2015), Yan et al. (2015), Omrani et al. (2015), Koronis et al. (2013)), characterized by the need to significantly limit the environmental impact associated with the production of materials commonly obtained from petroleum chemistry (plastics, synthetic rubbers, resins, synthetic fibers, paints, solvents, etc.) with irreversible release into the atmosphere of large quantities of carbon dioxide and other polluting substances.

This requirement is determined by both the objectives imposed by European standards in terms of recyclability of materials for automotive applications, and the objective of reducing the weight of the vehicle and therefore its consumption, always acting in the direction of reducing pollution. The vehicle's weight reduction is also particularly important in the modern development of hybrid and electric vehicles, which are characterized by high overall weight, due to the heavy contribution of energy accumulation systems (batteries).

In order to contribute to the development of high performance bio-composites, i. e. biocomposites for structural and semi-structural applications, in this work the mechanical properties of different green epoxy composites, have been evaluated. Particular attention has been paid to the optimization process of agave fibers, which consists in the proper choice of the variety (sisal), the position of the fibers in the leaf ("medium third" of agave leaves) and the age of the leaf itself (about 4 years), otherwise the appropriate selection of the extraction process (see Zuccarello and Zingales (2017), Zuccarello and Scaffaro (2017)). In detail, such optimized agave fibers have been used in order to implement suitable MAT and unidirectional fabrics. These particular fabrics have been subsequently used for the manufacture of biocomposites by means of suitable processes that allow the production of a high quality biocomposites, even with high volume fiber concentration. Moreover, short fiber biocomposites with 3D random orientation, obtained by simple mixing of short fibers (length of about 3-4 mm) and green epoxy matrix, have been analyzed. In particular, both the common hand lay-up procedure (and vacuum bagging technique) and a high-pressure molding process have been used in the work, which has been implemented by means of removable aluminum molds.

2. Materials: matrix and fibers

Taking into account previous studies, carried out by the same authors (Zuccarello and Zingales (2017), Zuccarello and Scaffaro (2017)), the attention of this work has been paid on the development of green epoxy matrix biocomposites reinforced by optimized sisal fibers.

These preliminary studies have been carried out on short-fiber biocomposites with random orientation (2D) and long-fiber unidirectional biocomposites made by green epoxy matrix and PLA, reinforced by different types of sisalana and marginata agave fibers. Such preliminary studies have shown that these materials have high mechanical strength, making them suitable for structural use. The mechanical characteristics can be further enhanced by the realization of unidirectional and angle-ply laminates obtained with hand lay-up process followed by an appropriate cure process characterized by the application of suitable pressure. In the studies reported in literature, the mechanical characteristics of the biocomposites reinforced by agave fibers are generally relatively low, due to both the limited quality of the composites (usually obtained without proper cure and/or post-cure processes) and the low volume fiber concentration (commonly lower than 20%).

In fact, as it is demonstrated in the present work, using natural fibers (never perfectly straight), in general high fiber concentrations and good quality can be obtained only by applying a suitable post-cure process characterized by the application of appropriate molding pressure

2.1. Green epoxy matrix

In accordance with the experimental results obtained in (Zuccarello and Scaffaro (2017)), a green epoxy resin with IHN type hardener (see technical data sheet reported in the reference list), produced by the Entropy Resin Inc. (CA) USA and called SUPERSAP CNR, has been considered. As widely shown in Zuccarello and Scaffaro (2017), this is an environmentally friendly matrix with mechanical properties comparable to those of a common epoxy resin obtained from the petrochemical industry.

Systematic pull-out tests on single fiber have also shown that such a green matrix has good compatibility with optimized agave fibers, with a relatively high adhesion index values, not less than 0.73 for fibers without any surface treatment (see references by Zuccarello and Scaffaro (2017)).

Fig. 1 shows the result of a specific tensile test performed on the particular batch of matrix used in this work, by means of a tensile test specimens prepared in accordance with the ASTM D638 – 14.

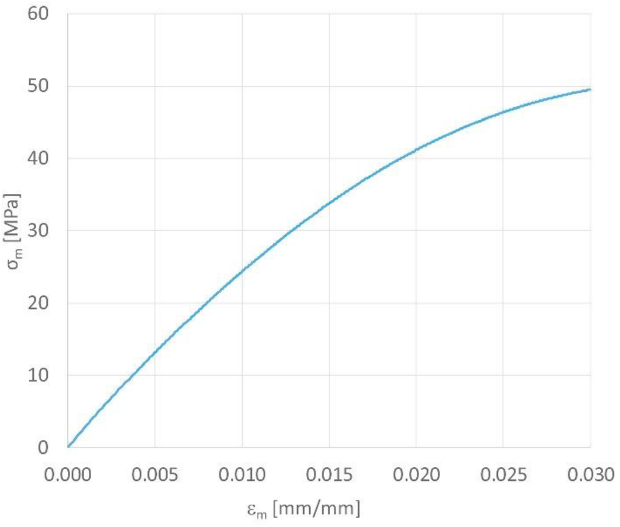

Fig. 1. Tensile test on the green epoxy matrix used in this work.

It is observed how this matrix exhibits an initial linear elastic behavior (up to a stress of about 40 MPa and strain about 2%) followed by a limited elasto-plastic phase until the ultimate stress $\sigma_{m,R}$ =50 MPa, that occurs at the ultimate strain $\varepsilon_{m,R}$ =3%. The Young modulus is E_m =2.58 GPa. The shear behavior, determined by means of Iosipescu shear tests, is governed by a larger plastic phase with an ultimate shear stress $\sigma_{m,R}$=35 MPa and by a shear modulus G_m =1.20 GPa (see Table 1).

Table 1. Properties of the green epoxy resin considered in this study.

$\sigma_{m,R}$ [MPa]	$\varepsilon_{m,R}$ [%]	E_m [GPa]	$\tau_{m,R}$ [MPa]	$\gamma_{m,R}$ [%]	G_m [GPa]
50	3	2.58	35	5	1.20

2.2. Optimized sisal fibers

In this work, agave sisalana fibers (sisal), optimized according to the specifications provided in Zuccarello and Zingales (2017), have been considered.

In particular, the agave fibers have been extracted from the medium third of mature leaves (4-5 years), considering only structural fibers (lying along the perimeter of the leaf) and excluding those located in the inner part of the leaf. I order to take high the eco-sustainability of the fibers, after the extraction process, they have not been subjected to any surface treatment (as mercerization or similar processes).

The mechanical properties of the fibers have been previously evaluated through single fiber tensile tests carried out in accordance with ASTM D3822 / D3822M – 14, by means of a 200 N material testing machine type BOSE Biodynamic Electroforce Test Instrument (see Fig. 2a) equipped with an optical extensometer (Fig. 2b); in detail, 8 specimens (bonded in a special paper frame) have been used.

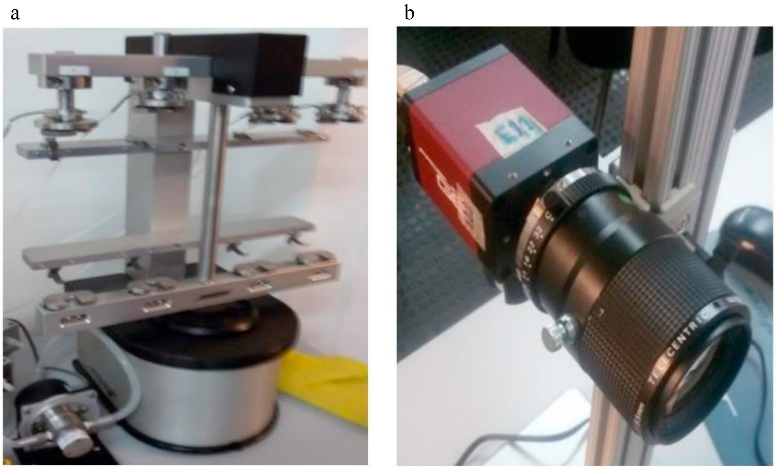

Fig. 2. *BOSE Biodynamic Electroforce Test Instrument*; (b) optical extensometer used for single fiber testing.

In order to evaluate the mechanical properties by means of single fiber tensile tests, it is necessary to accurately determine the cross-sectional area of each tested fiber. This measurement is characterized by objective difficulties related to the fact that the typical transversal section is not circular but has a "horseshoe" shape (see the micrograph reported in Fig. 3).

Unfortunately, several studies reported in literature (see as an example Singh et al. (1996), Mylsamy and Rajendran (2011)), show non-accurate results due to a coarse assessment of the cross-sectional area of each fiber. In order to overcome this problem, a reliable method of analysis based on a double measurement has been developed (see Fig. 3).

The method is based on two accurate mechanical and optical measurements: the first measurement (D1) is carried out with a high precision mechanical caliper with resolution of 0.01 mm that practically allows the determination of the minimum thickness of the fiber, while the second measurement (D2) is performed by means of a high-resolution digital image that allows, instead, the determination of the maximum thickness.

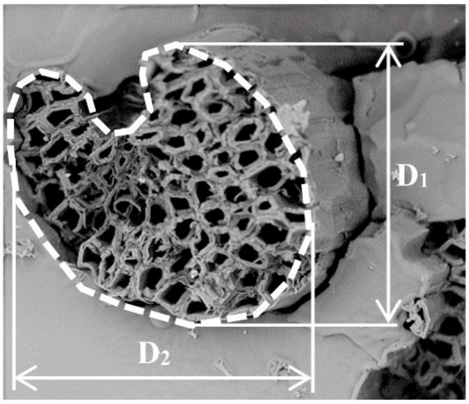

Fig. 3. Micrography of the cross-section of the agave fiber and measurements made with high precision caliper (D_1) and with photographic image processing (D_2).

The cross-sectional area of the fiber is determined through the following Eq. 1, by introducing a correction coefficient of 0.85 in order to take into account of the central groove.

$$A_f = 0.85\pi \frac{D_1 D_2}{4} \tag{1}$$

The values provided by Eq. 1 have been statistically verified with appropriate micrographic analyses performed on a large number of fibers; these results have generally indicated good average accuracy with errors not exceeding 5-6%. Fig. 4 shows the tensile curves relative to each tested specimen, along with the average curve, which has been marked with a dashed black line.

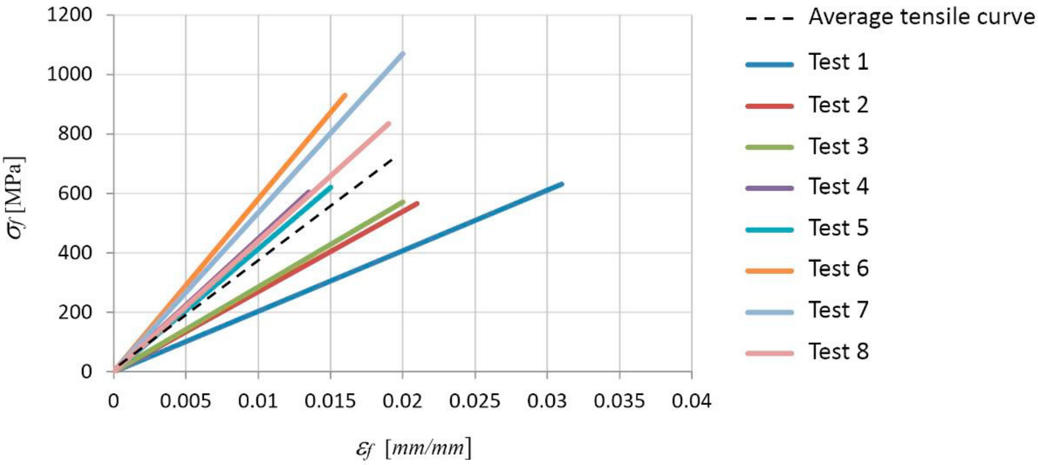

Fig. 4. Results of single fiber tensile tests (8 specimens tested).

From Fig. 4 a high scattering of the results is observed (ultimate stress in the range of about 800±30% MPa and Young modulus in the range of about 39.5±30% GPa). From the experimental results it has been possible to determine (see also Table 2) an average ultimate stress of about $\sigma_{f,R}$=690 MPa, an average Young modulus E_f=40

GPa and an average ultimate strain of about $\varepsilon_{f,R}$=1.8%.

Table 2. Average mechanical properties of the considered agave fiber.

$\sigma_{f,R}$ [MPa]	$\varepsilon_{f,R}$ [%]	E_f [GPa]
690	1.8	39.5

It is important to note that the ultimate strain is variable in a relative wide range, from about 1.3% to about 3.5%. In a properly designed composite, the failure of the component is strongly related to the failure of the fibers due to reaching their ultimate strain; therefore, a high variability of the ultimate strain of the fibers (see Fig. 4) results in a progressive damage of the composites and, consequently, the effective strength of the biocomposite materials will certainly be less than the value that can be estimated by assuming the simultaneous failure of all fibers (rule of mixture without a corrective coefficient). Fig. 4 shows that agave fibers always exhibit a linear elastic behavior with brittle failure. Experimental tensile strength values are in good agreement with those reported in literature, although the mean value (690 MPa) falls in the high zone of the range (350-700 MPa) reported in literature. This is mainly due to the preliminary optimization of the fibers (each fiber has been extracted from the “medium third” of the leaves, excluding the internal fibers). Finally, it is important to note that the fibers used in this work have not been subjected to any chemical treatment, i.e. they are strictly a renewable reinforcing material.

3. Manufacturing of biocomposites

In order to evaluate the mechanical performance of the different types of fiber-reinforced biocomposites that can be obtained by using the materials considered above, (1) biocomposites reinforced with Random Short Fibers (RSF), (2) biocomposites reinforced with Random Discontinuous Fibers (RDF) and (3) biocomposites reinforced with Unidirectional Long Fibers (ULF), have been realized by using proper manufacturing processes.

In detail, short fiber biocomposites have been obtained by using fibers with length of 3-4 mm, which corresponds in practice to approximately 10 times the so-called "critical length", i. e. the length that allows the complete load transfer (from matrix to fibers), see Zuccarello and Zingales (2017), Zuccarello and Scaffaro (2017). In fact, as it has been extensively studied in Zuccarello and Zingales (2017), for the couple of materials considered in this study the critical length is about 0.3-0.4 mm. Also, MAT fabrics, consisting of fibers having length of about 100 times the critical length, i. e. approximately 40 mm (actual length ranging from 40 to 80 mm), have been prepared in order to realize discontinuous fiber biocomposites. Moreover, stitched fabrics with lengths of 250-400 mm have been properly manufactured in order to realize unidirectional long fiber biocomposites.

It is useful to note that random short fiber biocomposites (RSF) can also be referred to as "3D random short fiber" biocomposites in order to underline that, due to the limited fibers length and the isotropy of the mixing process, as well as the dimensions of the specimens (3-4 mm at least), the fibers are randomly arranged in all directions.

On the other hand, randomly oriented discontinuous fiber biocomposites may be denoted with the term MAT (as is the case of similar composites reinforced by synthetic fibers) in order to indicate that the single ply consists of fibers randomly oriented in the laminate plane (2D). In the next section, a detailed description of the preparation process for each type of biocomposite has been reported.

3.1. Random short fiber biocomposites (RSF)

In the field of Polymer Matrix Composites (PMCs), randomly oriented short fiber biocomposites are typically obtained by molding process of fiber-matrix mixture, with a volume fiber fraction less than 30%. In the present work, the mechanical behavior of randomly oriented short fiber biocomposites has been studied by means of tensile tests carried out on rectangular specimens manufactured by using an aluminum mold (with disassembled elements) properly realized (see Fig. 5a) and covered with a release film.

The molding pressure has been applied by means of a 100 ton hydraulic press and, subsequently, all specimens have been cured at a temperature of 80°C for 1h. By means of this mold, short fibers biocomposites with a volume concentration of fibers V_f=30%, have been obtained (see Fig. 5b). In order to estimate the relative statistical distribution of the results, 5 specimens have been tested.

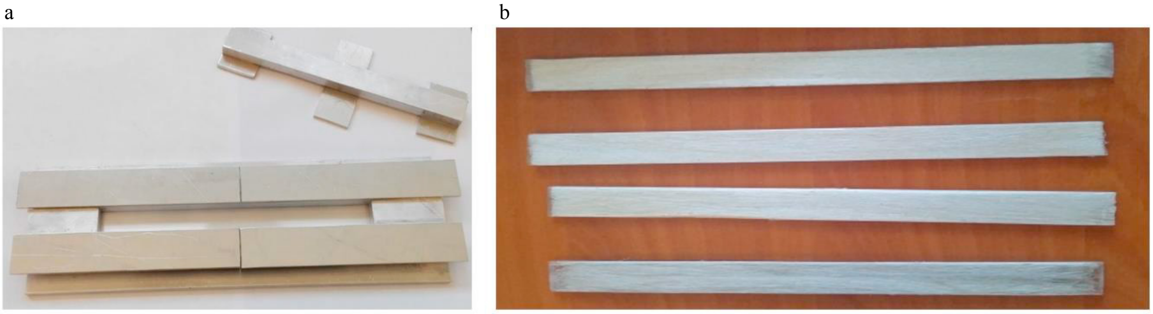

Fig. 5. (a) Mold used for the preparation of RSF biocomposites; (b) specimens after molding and subsequent cure process.

In more detail, biocomposites have been realized by pouring into the mold the fiber-matrix mixture obtained by manual mixing and, subsequently, by applying a pressure of 1.5 MPa that assure a good quality of the biocomposite (limited percentage of voids).

3.2. Random Discontinuous Fiber biocomposites (RDF)

Several studies on randomly oriented short fiber biocomposites are available in literature, whereas there are no studies on discontinuous fiber biocomposites produced with MAT fabrics. Fabrics made of natural fibers are not commercially available. Therefore, the fabrics have been properly obtained by random arrangement of the fibers with simultaneous nebulization of green epoxy resin, the same that has been subsequently used for the final manufacturing of the biocomposites.

Using this technique, MAT-type fabrics with a specific weight of 200 g/m^2, have been obtained (see Fig. 6a). These fabrics have been used for the subsequent lamination of biocomposite panels with a volume concentration of fibers V_f=30%. In more detail, the lamination process has been carried out in a mold of 200x350 mm (see Fig.6b). The specimen thickness, corresponding to the desired volume concentration of fibers, has been obtained by adjusting properly the molding pressure.

However, several initial tests have shown that it is not possible to obtain volume concentration of fibers more than 35%. Higher concentration, in fact, requires a molding pressure higher than 15 MPa, which results in transverse damage of the fibers and low biocomposite quality, due to the widespread lateral contact of the stacked fibers. Such phenomenon causes a significant reduction of the biocomposite mechanical properties, due to the premature progressive failure that start from these contact points between adjacent fibers (without interposed matrix), that behave like small cracks inside the biocomposite. Moreover, high operating pressures result in very high overall molding loads, which are almost prohibitive in the ordinary manufacturing of mechanical components; as an example, for the specimens shown in Fig.6b, a pressure of 15 MPa corresponds to an applied load of about 100 tons.

As is well known, this limitation is similar to that affects PMCs reinforced by synthetic fibers (fiberglass etc.). These latter, in fact, generally have a maximum volume fiber concentrations of about 25-30%, with recurrent values of about 15-20%. The molding pressure has been applied by means of a 100 ton hydraulic press and the RDF specimens have been cured at 80°C for 1h. Fig. 6c shows the biocomposite laminate after the cure process.

Fig. 6. (a) MAT fabric; (b) laminate inside the mold, before molding; (c) example of RDF laminate with V_f=30%.

3.3. Unidirectional Long Fiber biocomposites (ULF)

In order to evaluate the mechanical performance of unidirectional long fiber laminates, unidirectional fabrics have been suitably prepared in laboratory by aligning the fibers and fixing them by means of several transverse "stitching" realized at a mutual distance of about 100 mm (see Fig.7a). Such agave fabrics, in fact, are not commercially available as in the case of other fiber typologies (e.g. flax fibers). In particular, in the present work, unidirectional fabrics with a specific weight of about 180 g/m^2 have been obtained. These latter have been used in order to manufacture unidirectional laminates with a fiber volume fraction V_f= 30%, by means of hand lay-up and vacuum bagging technique (see Fig. 7b).

As an example, Fig.7c shows a biocomposite panel, from which several rectangular specimens have been extracted. Five specimens have been subjected to tensile test, carried out in accordance with ASTM standard [23].

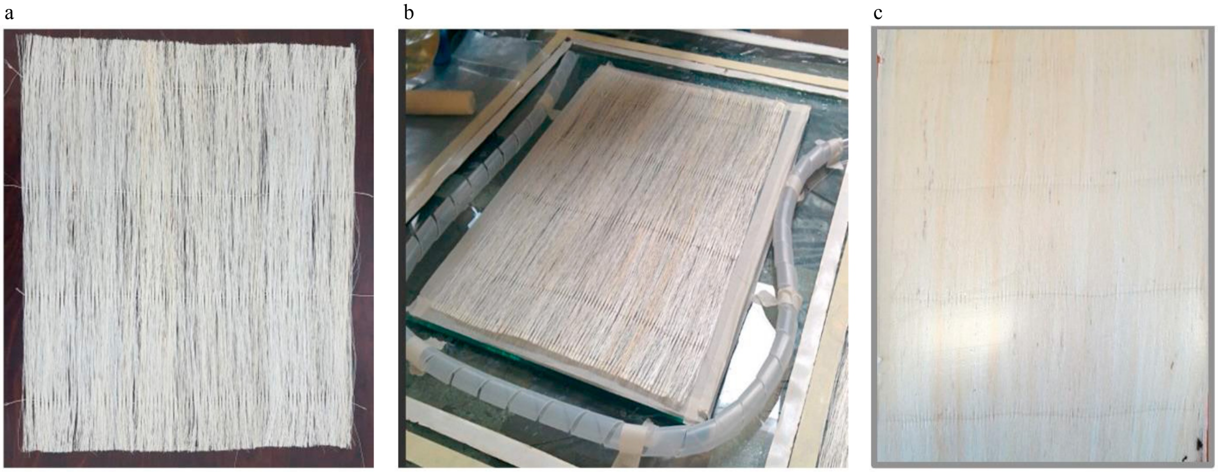

Fig. 7. (a) Unidirectional stitched fabric; (b) unidirectional laminate obtained by hand lay-up and vacuum bag technique; (c) example of unidirectional laminate.

4. Experimental tests

In accordance with ASTMD 3039/D 3039M 00, the main mechanical properties of the considered biocomposites (RSF, RDF, ULF) have been analyzed by means of tensile tests carried out by using a MTS 810 universal testing machine equipped with 100 kN load cell. Experimental test have been performed on rectangular specimens instrumented with MTS extensometer (Fig.8). As an example, Fig.8 shows a specimen for each of the three types of examined biocomposites, gripped on the material testing machine and ready for the tensile test.

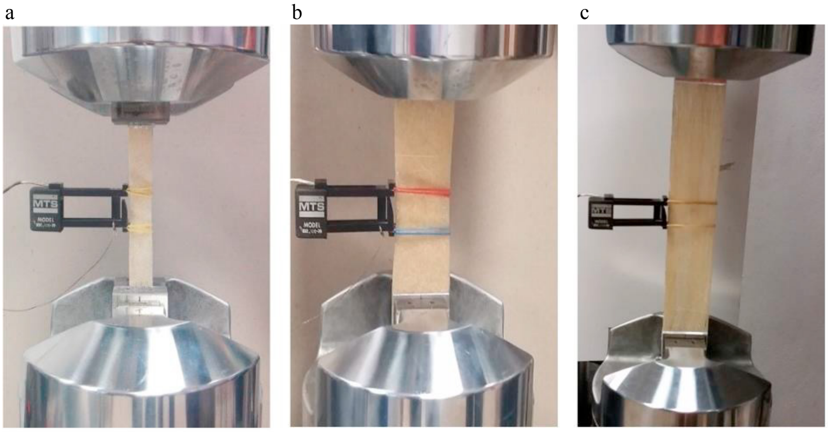

Fig. 8. Tensile test on (a) RSF, (b) RDF and (c) ULF biocomposite specimens.

4.1. Random Short Fiber biocomposites (RSF)

The following Fig.9 shows the tensile curves obtained by testing 5 RSF tensile specimens.

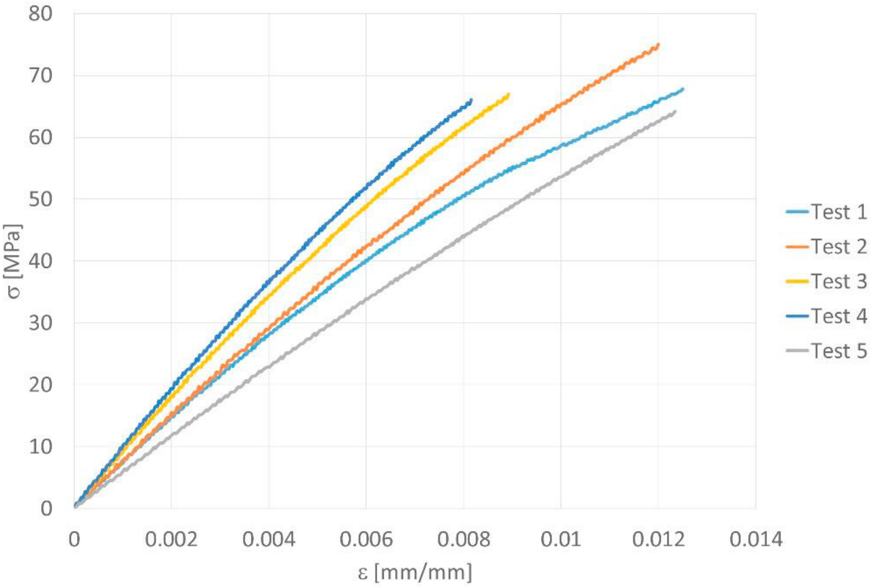

Fig. 9. Tensile curves for random short fiber (RSF) biocomposites.

From Fig. 9 it is observed that these biocomposites exhibit an almost linear elastic behavior with a trend characterized by a progressively decreasing stiffness up to failure. The decrease in stiffness is essentially related to the progressive failure of the fibers caused not only by the different strength of the fibers themselves (see dispersion of results in the case of single fiber tensile tests, Fig. 4) but, above all, by the different ultimate strains of the agave fibers. For the analyzed fiber volume ratio (V_f=30%), the tensile tests show that an average ultimate tensile strength of about 68 MPa has been reached that, compared to the matrix strength, allows to highlight that the fiber reinforcing leads to an increase of the ultimate strength of about 28%. Moreover, the tensile tests show a Young's modulus of about 6 GPa, that is about 2.5 times higher than the elastic modulus of the matrix. It will be interesting to analyze the strength and stiffness of the biocomposite for higher percentage of fibers volume fraction. However, in addition to possible performance gains (although higher volume concentration of fibers could affect the overall composite quality due to possible poor fiber wetting and concomitant high voids concentration), it is important to observe how unlike PMCs reinforced by synthetic fibers, in such biocomposites the increase of the fiber concentration leads to an appreciable reduction of the specific cost along with an increase of the eco-sustainability. Such result are due to the low cost of the fibers (approximately 0.4 €/kg) respect to the matrix one (4 €/kg or higher) and the higher eco-sustainability of the fibers respect to the matrix (partially bio-based epoxy). As an example, by passing from a fiber volume fraction V_f=30% to V_f=60%, it is possible to obtain a significant cost reduction of about 40% (from 2.92 €/kg to 1.84 €/kg).

4.2. Random Discontinuous Fiber biocomposites (RSF)

The following Fig.10 shows the tensile curves obtained by testing the 5 RDF specimens.

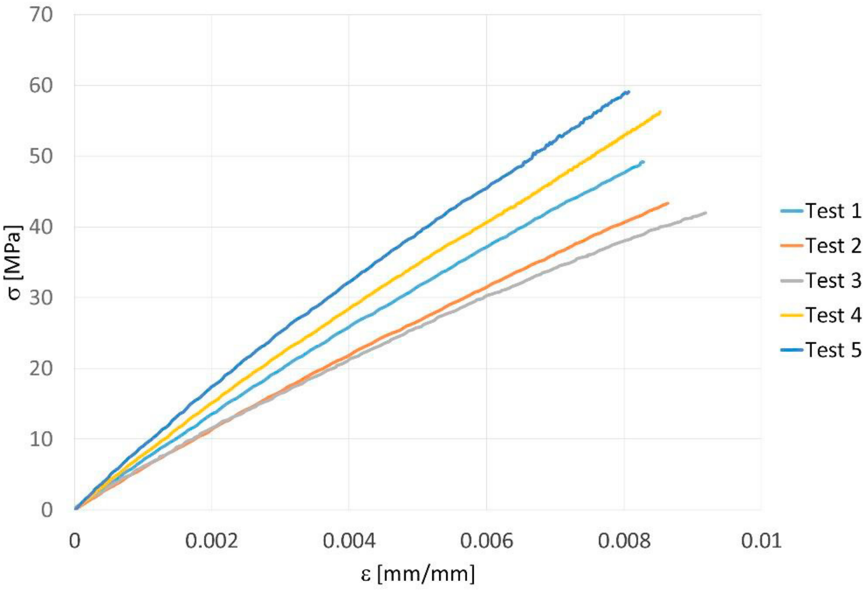

Fig. 10. Tensile curves for random discontinuous fiber (RDF) biocomposites.

In more detail, Fig.10 shows that these biocomposites exhibit a similar behavior to that observed for random short fiber biocomposites, i.e. a linear elastic trend with a slight final elasto-plastic behavior near failure.

A direct comparison between the curves of Fig. 9 and Fig. 10 shows that RDF biocomposites exhibit significantly lower resistance than RSF biocomposites. The average ultimate tensile strength of the analyzed RDF biocomposite is approximately 50 MPa, comparable to that of the matrix. The stiffness of the biocomposite, instead, reaches the same value that has been determined for RSF biocomposite. As above mentioned, the manufacturing of biocomposites with percentage fiber volume fraction above 30% requires very high pressures (more than 15 MPa), which is generally almost prohibitive for the production of mechanical components of medium and big dimensions; this result, together with the limited strength, constitute the main limitations to the use of these types of biocomposites.

4.3. Unidirectional Long Fiber biocomposites (ULF)

The mechanical characterization of unidirectional long fiber biocomposites has been performed by means of various specimens subjected to tensile test. In more detail, Fig. 11 shows the tensile curves obtained by testing 5 ULF specimens. It is shown how these unidirectional biocomposites exhibit a mechanical behavior significantly higher than that of the short and the discontinuous fiber biocomposites above considered, with average ultimate tensile strength $\sigma_{L,R}$ = 215 MPa.

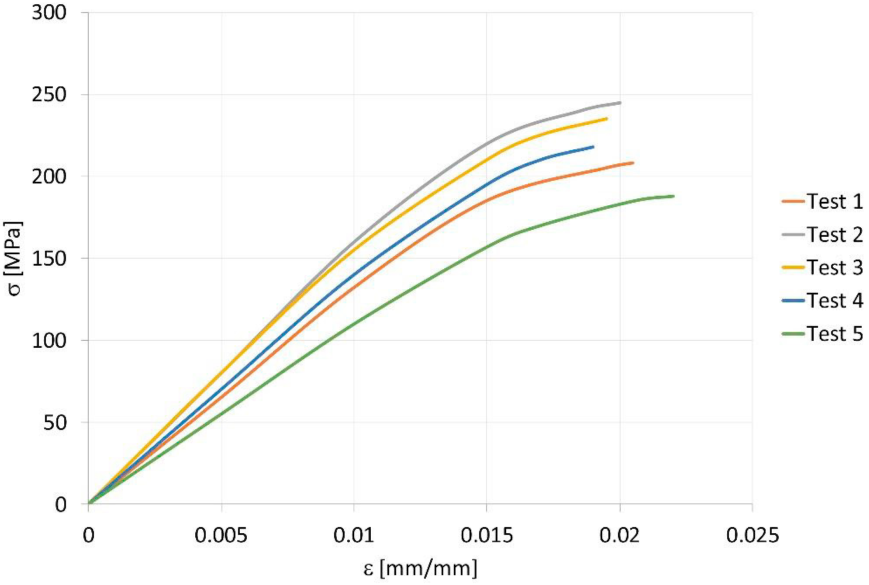

Fig. 11. Tensile curves for unidirectional long fiber (UFL) biocomposites.

It is remarkable to note that already for fiber volume fraction of 30% it is possible to obtain a biocomposite with high performance, i.e. with a tensile strength value comparable to the yield strength of several aluminum alloys, widely used in the aeronautical and automotive fields. The strength value is also comparable with that of Glass Fiber Reinforced Polymers (GFRP) and it is certainly higher to that of common fiberglass ($\sigma_{L,R}$=100-150 MPa).

The specific weight is very interesting with a value of 1350 kg/m3, i.e. about 1/6 the steel one, and about a half the aluminum alloys one. Moreover, this biocomposite has a lower specific weight (-30%) than a common GFRP (1900 kg/m^3), a CFRP (1540 kg/m^3, i. e. -10%) and a light AFRP (1400 kg/m^3, i. e. -5%).

In terms of specific strength, it is characterized by a ratio $\sigma_{L,R}/\rho$ = 0.16 kN m/g, which is not only higher than the steel ones (values between 0.058 and 0.106 kN m/g) but also higher than that of aluminum alloys one (about 0.15 kN m/g). For the examined volume concentration, the longitudinal Young's modulus was found to be about 15 GPa, which is much higher than that of a common fiberglass (E=8-10 GPa approximately).

Due to its low specific weight, the unidirectional biocomposite performance significantly improves in terms of specific stiffness. In fact, the specific modulus E_L/ρ = 11.1 kN m/g is about 60% lower than that of steel and aluminum alloys (about 26 kN m/g) and about twice that of a common fiberglass (about 6 kN m/g). Moreover, the specific modulus is slightly less than that of a common GFRP (about 15 kN m/g, i.e. about -25%)

5. Conclusions

The present study has been carried out in order to determine the mechanical behavior of biocomposites for semi-structural and structural applications based on eco-compatible (green) epoxy matrices reinforced by agave sisalana fibers (sisal). In particular, the performance of agave fibers has been appropriately optimized through a suitable selection of the leaves, the position of the fibers in the leaf, and the extraction process. In particular, several tensile tests on random short fiber biocomposites (RSF), random discontinuous fiber biocomposites (RDF) and unidirectional long fiber biocomposites (ULF) with a constant fiber volume fraction V_f=30%, have been carried out.

Experimental tests have shown that the manufacture of randomly oriented short fibre biocomposites is characterized by a tensile strength of about 68 MPa that, compared to the matrix one, allows an increase of the ultimate tensile strength of about 28%. In terms of stiffness, instead, it is possible to obtain better results: Young's modulus of about 6 GPa has been reached, i.e. about 2.5 times higher than the elastic modulus of the matrix. These results have been obtained by using fibers having length of about 3-4 mm, that allow the manufacturing of specimens with a 3D random distribution, i.e. with fibers arranged randomly in all directions of the component. Although the use of fibers of about 6 mm in length would allow a considerable improvement in strength (estimated of about 10%), this configuration has not considered in the work because it is not compatible with composite products usually characterized by thicknesses not exceeding 3-4 mm.

The study of discontinuous fiber biocomposites, potentially more performing than short fiber biocomposites due to the greater length of the fibers, has been carried out by means of the preliminary manufacturing of MAT fabrics obtained using the same eco-compatible epoxy matrix as adhesive. These agave fabrics are very interesting because they allow the manufacture of components of complex geometry by using a simple hand lay-up process.

The experimental analysis has shown that in such a biocomposite the 2D random orientation determines lower mechanical properties respect to RSF biocomposite and, above all, due to the high required molding pressures, it is practically not possible to obtain biocomposites with fiber volume fraction more than 35%. In more detail, with this type of reinforcement, the fiber volume fraction V_f=30% corresponds in practice to the critical fiber concentration and, therefore, it is not possible to obtain more resistant biocomposites than the matrix alone. The use of this type of biocomposites is limited to the cases in which the matrix strength is sufficient but matrix stiffness need significant improvement to limit properly the in service strains.

The study of unidirectional long fiber (ULF) biocomposites, carried out by means of the development of proper unidirectional stitched fabrics, has allowed to demonstrate that it is possible to obtain good quality biocomposites with high mechanical performance. In particular, the experimental evidence has shown that the vacuum bagging technique can be usefully used for the examined fiber volume ratio (V_f =30%), whereas for higher fiber concentrations, it is necessary to apply a suitable molding pressure.

As expected, experimental tests have shown that these materials exhibit performance higher than that of short and discontinuous fibers biocomposites, both in terms of strength and stiffness. These properties make the ULF biocomposites suitable to replace various technical materials, such as aluminum alloys, but also GFRPs and common fiberglass used in semi-structural applications.

The experimental results show that the specific strength, equal to about 0.16 kN m/g, is higher than that of the steel (values ranging from 0.058 and 0.106 kN m/g) or of aluminum alloys (about 0.15 kN m/g), widely used for structural applications. It is important to note that the specific stiffness of about 11.1 kN m/g is certainly higher than that of ordinary fiberglass (about 6 kN m/g), even if it is lower than that of steel and aluminum (about 26 kN m/g).

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