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Mechanical Characterization of Unidirectional Diss Fibre-Reinforced Epoxy

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ABSTRACT

As industries increasingly adopt composites for their superior stress resistance, the high cost and environmental challenges associated with their disposal remain significant concerns. Bio-composites offer a sustainable alternative by addressing these issues with better recyclability and lower environmental impact. This study explores the mechanical performance of a bio-composite featuring Diss fibres embedded in an epoxy matrix. We conducted tensile and Charpy impact tests to measure Young's modulus and impact energy, respectively. Different weight percentages of Diss fibres ($wt_D\%$) were used to prepare the specimens. The findings indicate that the Young's modulus of the bio-composite peaked at 1.30GPa with 20$wt_D\%$, beyond which it decreased. The incorporation of Diss fibres notably enhanced the tensile strength of the samples compared to the pure epoxy matrix. Additionally, impact energy increased with higher $wt_D\%$, reaching a maximum of 3.5J at 30$wt_D\%$. These results suggest that Diss fibres are a viable reinforcement material for developing greener composites.

Keywords: Ampelodesmos mauritanicus; Bio-composite; Diss; Impact test; Tensile test.

INTRODUCTION

Over time, composite materials have succeeded in occupying an important place in several fields, namely aerospace, aeronautics, automotive, biomedical, shipbuilding, sport, furniture... etc. [1], due to their high resistance to different kinds of solicitations coupled with remarkable lightness.

Despite these remarkable performances, composite materials are very expensive; they also cause a problem for the environment and waste disposal after achievement of lifetime, because their recycling is a complex operation due to the difficult separation of the different constituents, this is why there is currently a tendency to use natural fiber composites instead of composite materials of petroleum origin. Biocomposites are sustainable and could be fully recyclable, but could be more expensive if fully bio-based and biodegradable, they are also extremely sensitive to moisture and temperature [2].

Such problems have to be solved to improve bio-composites competitiveness over synthetic fiber composites, in this context, several research works have studied new bio-composites with an organic matrix or an organic reinforcement or both at the same time, some of these researches shows that the use of natural fibers requires a specific extraction method, and that the adhesion between fibers and matrix is often very weak. On the other hand, their sensitivity to moisture also causes a problem for their use.

By observing the rough leaves of the Diss which is a renewable and biodegradable plant, its use as a reinforcement component in an epoxy matrix is supposed to give a new bio-composite material with a strong adhesion between the epoxy matrix and the natural fibers.

In this work, tensile and Charpy impact tests were carried out on specimens made from Diss fibers held in an epoxy matrix to deduce the mechanical properties of the new proposed bio-composite material.

The use of natural fibers as reinforcement in polymer composites is still limited compared to synthetic fibers due to their low mechanical properties as a result of a bad adherence between the natural fibers and polymer matrices, also the poor moisture resistance makes them less durable. These drawbacks are due to the presence of hydroxyl and other polar groups in natural fibers which make them hydrophilic in nature, a main reason for the weak adhesion to hydrophobic matrices and led bio-composites to be futile in wet conditions [3,4].

To improve their performances and expand their applications; many researchers experimented with natural fibers of plant origin such as Abaca, Areca, Bagasse, Bamboo, Banana, Coir, Cotton, Flax, Hemp, Henequen, Jute, Kapok, Kenaf, Oil and Date Palm, Pineapple, Ramie, Rice husk, Sisal, Soybean, Wood, … [1,2,5–7], The mechanical properties exhibited by these composites make them suitable for low load applications such as window panels, decorative items, cushioning pad, fishing rod, internal parts of an airplane, lampshades, food trays & interior paneling, etc. Thus these composites can replace the most conventionally used materials in those applications and enhance the overall quality of the product [8].

Fibers are extracted from various parts of the plants like stem, leaf, bast, flower, and fruits. Among various parts of the plant, majorly leaves were discarded as waste in most cases. The fibers extracted from the leaves have equivalent strength when compared with those extracted from other parts of the plant [1].

Legrand et al. investigated in 2020 water absorption capacity, moisture content, real density, porosity, chemical composition, chemical structure, and thermal behavior of fiber extracted from the bark of Cola Lepidota (CL) plant, grown in the flora of the Southern part of Cameroon. It was discovered that the new fiber has relatively low moisture content and water absorption capacity similar to those of other investigated natural fibers such as flax, sisal, coconut, hemp, and jute. Its porosity was found appropriate for composite production and the fiber was found to be thermally stable up to 230°C [9].

Chen et al. investigated the influence of light fiber modification and fiber loadings (5–15wt%) on the thermal, mechanical and physical properties of post-consumer high-density polyethylene (pHDPE)/sugarcane bagasse (SB) bio-composites. They have found that the stiffness of bio-composite increased linearly with fiber loading, experimental results show that Young's modulus has reached 515.5MPa while that of pHDPE is only 302.2MPa [10].

Bahrain et al. investigated the mechanical, physical, and morphological properties of the benign silicone composites from sugar palm fiber and silicone rubber with sugar palm (SP) filler contents ranging from 0% to 16% by weight (wt%). Based on the uniaxial tensile tests, it was found that the increment in filler content led to higher stiffness. Via dynamic mechanical analysis (DMA), the viscoelastic properties of the silicone bio-composite showed that the storage modulus and loss modulus increased with the increment in filler content [11].

Ampelodesmos mauritanicus, also known as Diss, is a species of monocotyledonous plants largely presented in the Algerian territory that requires a very small amount of water to grow, it is an attractive feedstock that can grow on less fertile or marginal lands, requiring a modest pest and disease management [12], it is a robust, perennial herbaceous plant, with leaves that are rough to the touch and can reach 2 to 3m in height [13]. It grows in a wild state around the Mediterranean, North Africa and dry areas of Greece and Spain [14],

The generic name Ampelodesmos is formed from two Greek roots: ampelos, "vine", and desmos, "tie", in reference to its ancient use as a kind of string to tie the vine [15], it was also used as a building material in the past because of its mechanical and hydrous qualities [14].

Maghchiche has characterized fibers extracted from the Ampelodesmos mauritanicus plant based on the measurement of the morphological structure, chemical analysis, infrared spectroscopy, X-ray diffractometry and thermal analysis, Table 1 shows that the Diss plant has a very variable mineral composition with a very high presence of silica [13].

To understand the reason behind the surface roughness of the leaves, a Diss leaf was observed using a scanning electron microscope (SEM), after being magnified to several scales; it has turned out that there are thorns on the surface of the leaves as shown in Figure 1.

Remila et al. enhanced the performance of biocomposites based on a blend of PHBV and PLA and diss fibers as reinforcement by incorporating PHBV-g-MA as a compatibilizer improves the interfacial adhesion between the

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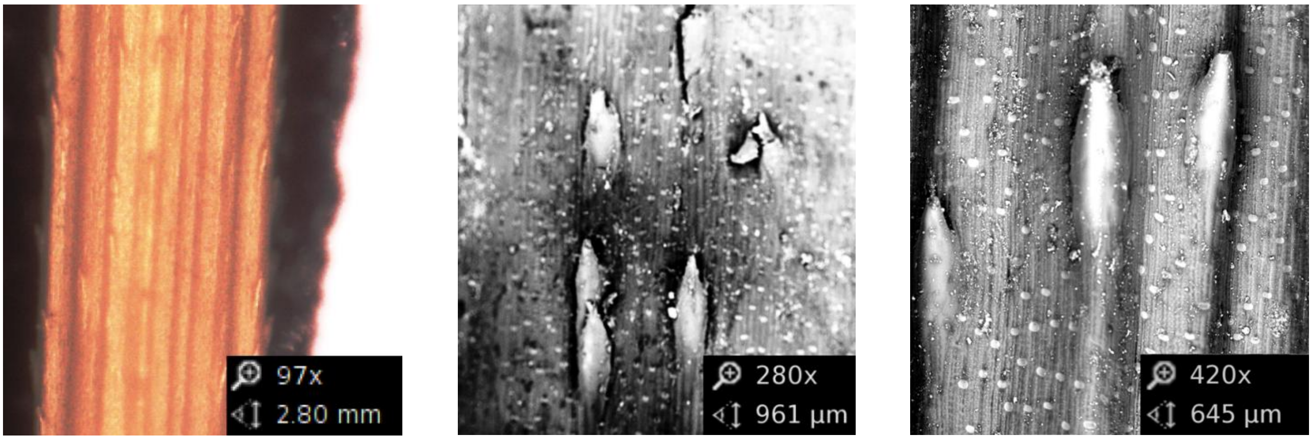
PHBV/PLA matrix and the diss fibers, leading to better mechanical properties, such as increased tensile strength and impact resistance. The addition of diss fibers further enhances the composite's stiffness and thermal stability [16].

Kharchi et al. explored the use of citric acid treatment as a novel method to enhance the properties of composites made from Ampelodesma mauritanica fibers and poly-lactic acid (PLA). They demonstrated that the treatment increases the surface roughness and hydrophobicity of the fibers, as a result, the composites exhibit improved thermal stability, tensile strength (4.680 Gpa), tensile strength (48.90 Mpa), and and elongation at repture (2.52 %) [17].

Karek et al. have used Diss fibers to evaluate the mechanical behavior to impact test of biocomposite formed of starch Glycerol 40% matrix reinforced by Diss fibers, it was found that the bio-composite with 5% of Diss fiber reinforcement (SG40/RF5) had better results compared to the rest of the combinations; the absorbed impact energy was about 31.25KJ/m², which is 2.1 times higher than that of SG40 matrix alone and 1.3 times higher than that of 10% fiber reinforcement [18].

Table 1: Mineral components of Ampelodesmos mauritanicus [13]

Elements	SiO_2	CaO	MgO	K_2O	Na_2O	Fe_2O_3
%	72.25	4.50	1.45	3.60	0.70	2.31



(a) (b) (c)

Figure 1. Surface of the Diss leaves observed by SEM imaging magnified: a) 97×, b) 280× and c) 420×

MATERIALS AND METHODS

a) Fiber preparation

Because the Diss leaves are long and their surface on one side is rough, the preparation of the Diss fibers was simple; after cleaning the leaves and letting them dry for more than 3 months.

No chemical treatment has been carried out or any machine was used in the extraction process which means that the production of this bio-composite will be easy and less expensive than many other composites and bio-composites.

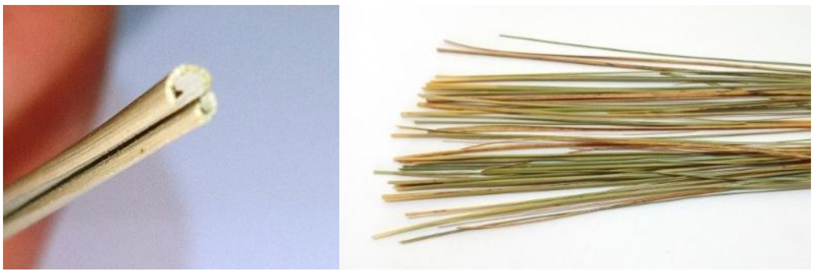


Figure 2. A rolled-up leaf on the left and a bundle of Diss fibers after preparation on the right

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b) Molding

The elaboration of the test specimens was first by using a simple mold composed of three superimposed pieces of flat iron 50×5mm with a length of 200mm, the middle piece contains an oblong hole where fibers are deposited after having been immersed in epoxy.

The preparation consists in covering the two parts (upper and lower) with an aluminum foil to facilitate the separation of the parts of the mold during the extraction of the specimen. Then the medium part is hold with the lower part of the mold using a tape.

The Diss fibers are then cut to the appropriate length, after that the epoxy is prepared by mixing, as needed, a quantity of epoxy with 1% hardener. Fibers are then immersed the in epoxy and disposed in the mold in a way to get as much as possible a homogeneous distribution of the fibers, the rest of the mold is then fill up with epoxy.

After that, the specimen is covered by the upper part of the mold and pressed to get rid of the excess epoxy. Four hours later, the specimen is extract before it gets hardened and let it on a flat surface.

After mastering this technique, another mold was made (Figure 3) to produce 4 specimens at one time, all the specimens are of dimensions 150×20×4mm.

For impact test specimens, median piece of the mold is replaced by another one of 8 specimens of dimensions 55×12×10mm (Figure 3), the notch is made manually after the specimens harden.

Figure 3. Mold of tensile specimens (left) and median piece of mold for impact test specimens (right)

c) Testing equipment

The tensile tests were carried out in CRM (Mechanical Research Centre - Constantine) on the EUROTEST-300 tensile test machine of the IBERTEST Spain brand, a universal machine of 300kN traction capacity controlled by a computer. Impact tests were carried out on a KARL FRANK GmbH (Germany) Charpy impact test machine (type 53565) of the laboratory of the mechanical engineering department at the University of Ouargla, both testing machines are shown in Figure 4.

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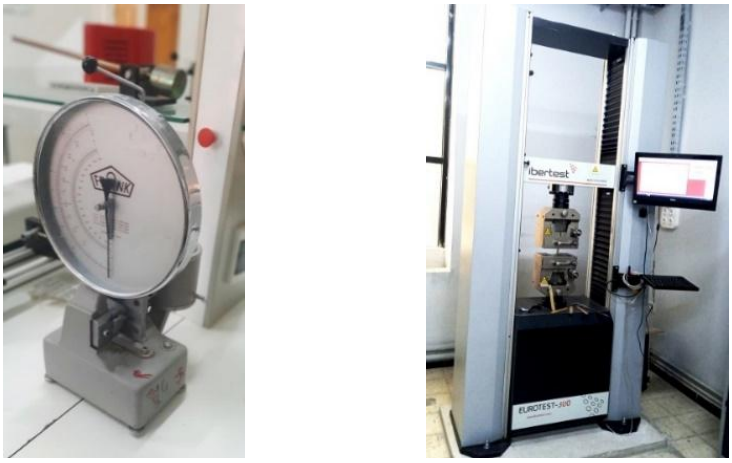

(a) (b)

Figure 4. Testing machines: a) IBERTEST - EUROTEST-300 tensile test machine (Spain) and b) KARL FRANK Charpy impact test machine (type 53565) (Germany)

RESULTS AND DISCUSSION

a) Tensile Test

Starting by elaborating on the specimens using the first mold of one specimen at one time, the oblong hole was first filled with the maximum quantity of long Diss fibers; the maximum weight was 6g. After elaborating four specimens, the amount of Diss fibers is reduced to 5g for four other specimens, and reduced again to 4g for four other specimens. Figure 5 shows some samples of the elaborated specimens.

Figure 5. Samples of tensile test specimens with different weight percentage of Diss fiber after being tested

After replacing the mold by the one shown in Figure 3 to accelerate the process of specimens' elaboration, the maximum quantity of Diss fibers that could be filled in each hole of every oblong was 4g, so 4 specimens were made of 4g, 3g, 2g and 1g of Diss fibers. Expecting that the resistance will be better when the density of fibers is greater, more specimens of 4g of Diss fibers were elaborated.

The composition of each specimen, its weight and the results of the tensile tests (which were conducted according to the ASTM D 3039/D 3039M – 00 standard [19]) are shown in Table 2.

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The results have shown an elastic behavior of all specimens, Figure 6 shows the stress-strain curves of some specimens of various weight percentages (wt_D%) of Diss fibers; contrary to what was expected, the maximum Young's modulus was not recorded for the maximum of the Diss fiber weight.

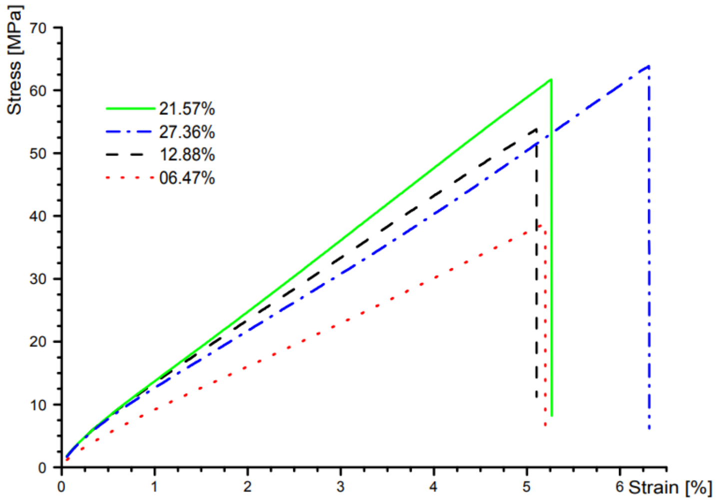

Figure 6. Stress-strain curves of some specimens

Table 2: Specimens specifications and tensile test results

N°	Cross section A [mm²]	Specimen weight M [g]	Quantity of Diss fibers M_D [g]	Weight of Diss fibers wt_D [%]	Elastic resistance Re [MPa]	Elongation ΔL [mm]	Young's modulus E [GPa]
1	80	14.82	0.00	0.00	25.04625	2.38078	0.59469
2	80	14.89	0.00	0.00	23.16375	2.41577	0.53304
3	80	14.91	0.00	0.00	26.69625	2.40946	0.62979
4	80	15.70	1.00	6.37	39.10875	2.44668	0.85996
5	80	15.46	1.00	6.47	38.86500	2.60199	0.77836
6	80	15.18	1.00	6.59	42.79125	2.51770	0.95405
7	80	15.59	2.00	12.83	43.42875	1.79081	1.37189
8	80	15.53	2.00	12.88	53.83875	2.55285	1.13340
9	80	15.49	2.00	12.91	43.83375	1.96714	1.19816
10	80	15.04	2.00	13.30	50.17125	2.65356	1.02661
11	100	23.09	4.00	17.32	48.28200	2.59821	0.95379
12	100	22.06	4.00	18.13	47.09700	2.20519	1.11533
13	100	21.91	4.00	18.26	44.31900	1.99549	1.20016
14	80	15.96	3.00	18.80	58.67625	2.35724	1.30429
15	80	15.43	3.00	19.44	55.22250	2.37140	1.25206
16	100	23.77	5.00	21.03	61.80600	2.63529	1.21461
17	100	23.18	5.00	21.57	53.90400	2.25519	1.29575
18	100	23.12	5.00	21.63	50.42400	2.31355	1.11192
19	100	23.20	6.00	25.86	60.61500	2.47004	1.30273
20	100	22.96	6.00	26.13	53.82600	2.42478	1.13603
21	80	15.25	4.00	26.23	67.48125	3.16526	1.04764
22	80	14.73	4.00	27.16	70.24500	3.06747	1.20155

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23	80	14.72	4.00	27.17	62.20125	3.02936	1.07461
24	80	14.62	4.00	27.36	63.98625	3.16016	1.02476
25	80	14.44	4.00	27.70	50.85750	2.36782	1.12091
26	80	14.20	4.00	28.17	59.61375	2.62493	1.18634

To better define that, Figure 7 shows the variation of Young's modulus function of Diss fiber weight parentage, it is clear that the maximum Young's modulus is reached for approximately 20wt$_D$% of Diss fiber weight parentage.

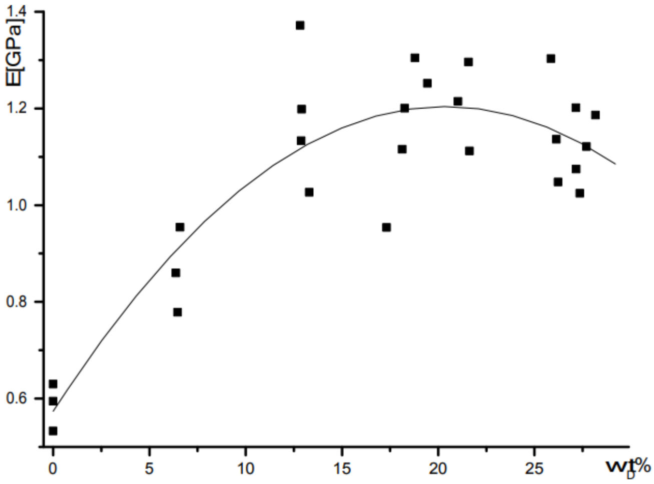

Figure 7. Young's modulus function of Diss fiber weight parentage

For Diss fiber weight parentage greater than 20wt$_D$% Young's modulus decreases as much as more fibers are used, this can be explained by the lack of epoxy between the fibers, the fibers (of low density) occupy a large space of the total volume of the specimen, thus reducing the possibility for the matrix to bring them together. Greater strain was also recorded when the amount of Diss fibers is more than 20wt$_D$% of the specimen weight, this result in the slippage between fibers due to the lack of epoxy.

Upon examination of the cross-section of the specimens subjected to tensile testing, as depicted in Figure 8, it is evident that the failure occurred in a section perpendicular to the longitudinal axis of the specimen. The majority of the fibers were severed in this section, and there was no indication of fiber slippage, which suggests strong adhesion between the fibers and the matrix.

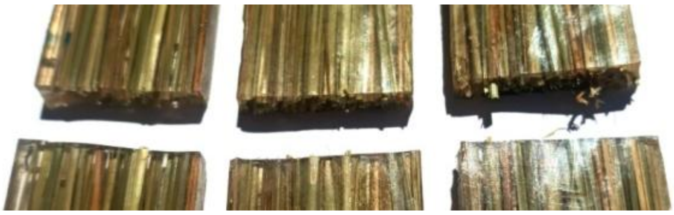

Figure 8: Cross-section of tested specimens in tensile test

b) Charpy Impact Test

The maximum quantity of Diss fibers that can be filled in each one of the 8 rectangular holes of the middle piece of the mold shown on the left of Figure 3 was only 2g, thus, 48 specimens were elaborated with different amounts of Diss fibers (from 0g to 2g by an increment of 0.2g). Specimens' composition and absorbed impact energy are shown in Table 3.

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Table 3: Charpy impact test results

N°	M_D [g]	M [g]	wt_D [%}	E [J]	N°	M_D [g]	M [g]	wt_D [%}	E [J]
01	0.0	7.53	0.0000	0.66	**23**	1.0	7.74	12.9199	2.20
02	0.0	7.61	0.0000	0.82	**24**	1.0	7.50	13.3333	2.23
03	0.0	7.68	0.0000	0.54	**25**	1.2	7.61	15.7687	2.15
04	0.0	7.60	0.0000	0.50	**26**	1.2	7.43	16.1507	2.27
05	0.2	7.16	2.7933	1.09	**27**	1.2	7.11	16.8776	2.10
06	0.2	7.10	2.8169	0.66	**28**	1.2	7.49	16.0214	2.44
07	0.2	7.57	2.6420	0.67	**29**	1.4	7.08	19.7740	2.05
08	0.2	6.62	3.0212	0.72	**30**	1.4	6.77	20.6795	2.90
09	0.4	7.64	5.2356	0.85	**31**	1.4	6.69	20.9268	3.05
10	0.4	7.61	5.2562	0.99	**32**	1.4	7.01	19.9715	3.01
11	0.4	7.74	5.1680	1.09	**33**	1.6	7.57	21.1361	2.75
12	0.4	7.28	5.4945	1.14	**34**	1.6	7.40	21.6216	2.54
13	0.6	7.62	7.8740	0.85	**35**	1.6	7.29	21.9479	2.41
14	0.6	7.55	7.9470	1.10	**36**	1.6	7.75	20.6452	2.75
15	0.6	7.49	8.0107	1.05	**37**	1.8	7.20	25.0000	3.05
16	0.6	7.87	7.6239	1.11	**38**	1.8	7.22	24.9308	3.39
17	0.8	7.12	11.2360	1.20	**39**	1.8	7.01	25.6776	2.72
18	0.8	7.55	10.5960	1.91	**40**	1.8	7.09	25.3879	3.25
19	0.8	7.34	10.8992	1.15	**41**	2.0	7.28	27.4725	3.50
20	0.8	7.34	10.8992	1.50	**42**	2.0	7.37	27.1370	3.21
21	1.0	7.61	13.1406	2.32	**43**	2.0	7.07	28.2885	2.93
22	1.0	7.19	13.9082	1.94	**44**	2.0	6.72	29.7619	3.28

M_D: Fibers weight, M: Specimen weight wt_D: mass fraction of Diss fiber, E: Impact energy

Figure 9 shows some of the specimens of different compositions (after being tested), specimen number 5 is one of four specimens that have a small quantity of Diss fiber reinforcement, while specimen number 44 is one the most filled specimens with Diss fiber, which have absorbed more than 3 Joules of the impact energy without being broken.

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Figure 9. Samples of impact test specimens with different weight percentages of Diss fiber after being tested

Figure 10 reveals that this green composite, formed of Diss fibers held in an epoxy matrix absorbs impact energy better when it contains more Diss fibers, it seems that its ability to absorb the impact energy increases linearly when the weight of Diss fibers increases, but a maximum of 30wt$_D$% Diss fiber reinforcement was reached, not more. For that; the studied bio-composite is ductile compared to the virgin epoxy.

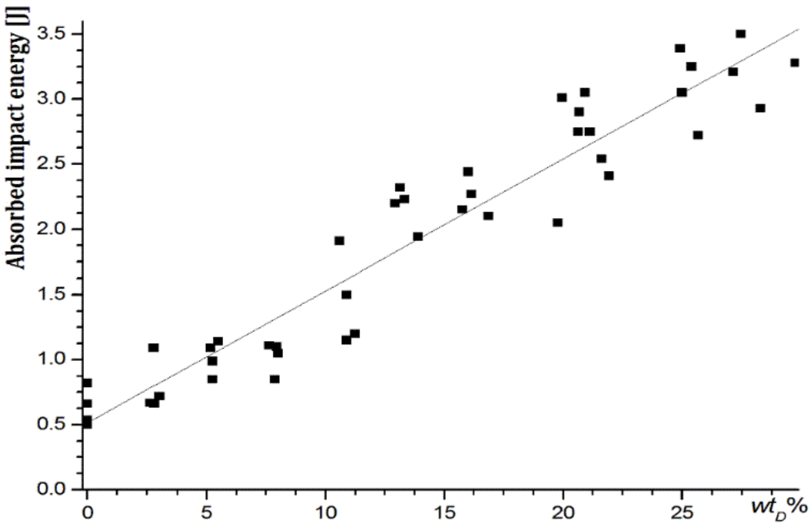

Figure 10. Impact energy variation in function of Diss fiber density

Figure 11 displays the cross sections of specimens that underwent Charpy impact testing with varying quantities of Diss fibres. The figure illustrates that the distribution of fibres is not uniform across the cross-section, with some areas having a higher concentration of fibres than others.

This non-homogeneity may have an impact on the mechanical properties of the material. Moreover, the figure indicates that with an increase in Diss fibers, the cross-section of the specimens becomes more deformed. This observation suggests that a higher concentration of fibres results in a greater amount of absorbed energy during the impact testing process.

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Figure 11: Cross Sections of Charpy-Impacted Specimens.

In addition, the cross-sectional analysis reveals that the fibres are cut at different locations, implying that the impact force caused the fibres to fracture at varying points along their length. Nevertheless, it is worth noting that the fibres still adhere to the epoxy matrix, indicating good interfacial bonding between the fibres and the matrix. Strong interfacial bonding is critical for the mechanical performance of composite materials since weak bonding can cause material failure at low-stress levels.

CONCLUSION

This study is a contribution to green composites promotion where a mechanical characterization of a bio-composite formed of long unidirectional Diss fibers as reinforcement in an epoxy matrix was done; Young's modulus and impact energy were defined through tensile and Charpy impact tests respectively. The studied specimens were of different fiber weight percentages. Results show that Young's modulus of the studied bio-composite reaches its maximum value of 1.30GPa for 20% of reinforcement weight, then decreases for fiber reinforcement of more than $20wt_D\%$. Compared to the virgin epoxy matrix Young's modulus (0.57GPa), this bio-composite has shown considerable tensile resistance amelioration by using Diss fibers as reinforcement. Results show also that absorbed impact energy increases when the weight of Diss fibers increases, but a maximum of $30wt_D\%$ of Diss fiber reinforcement was reached, which means that this green composite is even more ductile compared to the virgin epoxy and will better resist shocks and cracks propagation. Such largely presented plant around the Mediterranean and regarding these results, Diss can be an attractive feedstock for green composites production.

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