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COMPOSITES THEORY AND PRACTICE

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EXPERIMENTAL CHARACTERIZATION OF HEMP WOVEN FABRIC REINFORCED EPOXY RESIN COMPOSITES PRODUCED WITHOUT HEAT TREATMENT

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In the field of composite materials there is growing emphasis on environmental impacts, resulting in the replacement of synthetic-based components with bio-based components, and in particular, attention to the production process. The focus of the paper is the production of a composite reinforced with natural fibers, which can find applications in the construction field as the reinforcement of wooden structural elements, or as a skin for boards or sandwich panels. In this sector, it is not necessary to achieve very high mechanical performance as in the automotive sector. On the other hand, the cost of the product must be kept low and the production process simple. The proposed composite was prepared with an epoxy resin matrix reinforced with a bidirectional woven fabric made of hemp fibres without any heat treatment. The composites were hand laminated and manufactured by cold moulding to reduce energy consumption. To optimize the behaviour of the composite, various specimens were manufactured, and factors such as the curing pressure, quantity of resin and layer orientation were modified. Tensile strength tests were conducted on specimens according to the ASTM D3039 standard.

Keywords: **mechanical properties, hemp fibre, epoxy resin, bidirectional woven fabric, natural fibre reinforced composites, cold moulding**

INTRODUCTION

Increased awareness about environmental impacts has resulted in a reduction in synthetic-based elements in composite material reinforcement [1]. As a result, the incorporation of cellulosic fibres such as flax, hemp, or kenaf has gained significant attention in recent years [2, 3].

The use of natural fibres instead of synthetic ones offers undoubted advantages: lower economic and environmental costs [4], low-density [5], easy availability, good thermal and acoustic insulation, in addition to good resistance and stiffness characteristics [6, 7]. There are some drawbacks which include poor adhesion at the interface between the fibres and the resin matrix, limited thermal stability, a hydrophilic nature that might cause dimensional instability and poor compatibility, degradation of the mechanical properties above 180 °C - 200 °C, and great variability of the properties due to the natural origin of the material [8].

Hemp fibre is considered one of the most promising natural fibres for the production of composite materials. The plant does not require the use of fertilizers or pesticides, and it is relatively resistant to parasite attacks, resulting in a positive environmental impact during cultivation. In addition, hemp crops yield more fibers per hectare compared to other crops. For instance, hemp yields approximately 220/365 kg/hectare of fibers, whereas flax yields around 150/210 kg/hectare. Hemp holds deep historical, social, and agricultural roots in European countries like Italy. Additionally, hemp fibre exhibits good mechanical properties, with a tensile strength ranging from 550 to around 1240 MPa, Young's modulus between 25 GPa and 70 GPa and a maximum deformation at failure from 1.0 % to 4.2 % [9-14]. The variability in these properties can be attributed to various factors such as cultivation conditions (soil quality, seed density, climatic and weather conditions, species), harvesting techniques, and fibre extraction methods.

The mechanical properties of hemp fibres are influenced by the diameter of the fibres [9]. In particular, the tensile strength, elastic modulus, and strain decrease significantly as the diameter of the fibres increases.

Typically, thermoplastic, or thermosetting resins are used in composite materials. Thermoplastic resins offer many advantages like low processing costs, design flexibility, and ease of moulding complex parts. However, they require high processing temperatures which must be limited to avoid the thermal degradation of natural fibres. To avoid processes with high temperatures, thermosetting resins can be used. Epoxy resin, a thermosetting resin, is one of the most used and provides good mechanical properties for the composite [8, 10]. Natural fibre composites made with thermosets are highly solvent-resistant, tough, and creep-resistant. To make production easy and optimize reinforcement architectures, textile preforms are usually used [11, 12]. Another crucial factor is the adhesion capacity between the matrix and the fibres, which significantly impacts the mechanical properties of the composite. In the case of natural fibres, the degree of adhesion can be enhanced through the chemical process of alkalization [13].

The aim of this paper is to produce, characterize and optimize a composite material reinforced with natural fibres, intended for applications in the construction field, for example as a skin for panels made of agriculture waste or other natural crops [15], skins for sandwich panels [16] or to reinforce wooden structural elements such as beams or columns [17]. For these applications, materials and production processes characterized by a low cost need to be employed. Hemp fiber was chosen as the reinforcement material not only for its good mechanical properties but also for its lower price compared to other fibres like flax.

To significantly reduce energy costs, i.e. the economic and environmental costs of the finished product, the composites were produced by means of a cold pressing process, without heat input. The hemp fabric used consisted of bidirectional woven, equal fibres aligned along the warp and the weft directions. Woven fabric was chosen because it is easy to laminate compared to short fibres or fibre bundles and facilitates the manufacturing process, thus accelerating the production process. A bidirectional fabric was chosen because the desired material was one with the same mechanical properties in the two principal directions. Different types of composites were manufactured by varying some variables: the mould pressure, layer orientation, and the quantity of resin used. The aim is to find the production process parameters that provide the composite with the best ratio of mechanical properties. The produced composites were subjected to tensile tests. The tensile tests were conducted according to the ASTM D3039 standard [18].

MATERIALS AND METHODS

Hemp fabric and epoxy resin

Hemp fibres provided by Linificio e Canapificio Nazionale were utilized as the reinforcement in the form of Satin Balance bidirectional woven fabric, consisting of 100 % hemp fibres, with the specifications listed in Table 1.

Micrographs of the hemp fabric and a single strand of hemp yarn are presented in Figure 1.

The epoxy resin used was SX10 EVO, provided by Mike Compositi, which can harden at room temperature. It exhibits the following mechanical properties: tensile strength ranging from 55 MPa to 65 MPa, Young's modulus of 2800 MPa to 3300 MPa and maximum tensile deformation of 2 % - 3 % at failure.

TABLE 1. **Physical properties of hemp woven fabric used**

Woven thickness	1.6 mm
Woven warp density	6.5 yarns/cm
Woven weft density	6.0 yarns/cm
Woven density per unit area	350 g/m^2
Twist level	39 turns/m
Hemp fibre density	1.48 g/cm^3
Tenacity at break of yarns before weaving	24 cN/Tex [10]
Tenacity at break of yarns after weaving	17 cN/Tex [10]
Longitudinal tensile strength of fibres (σ_f)	429 ± 10.2 MPa [19]
Longitudinal modulus of elasticity of fibre before weaving at strain between 0.0 % and 0.1 %	62 GPa [10]
at strain between 0.3 % and 0.5 %	36 GPa [10]
Longitudinal modulus of elasticity of fiber after weaving at strain between 0.0 % and 0.1 %	68 GPa [10]
at strain between 0.3 % and 0.5 %	29 GPa [10]

a) b)

Fig. 1. Micrographs of: a) hemp woven fabric, b) single hemp strand

Production of hemp/epoxy resin composites

The composite plies were manually laminated and then manufactured by moulding at room temperature, at approximately 25 °C. Working at room temperature, in addition to reducing the production costs, prevents the degradation of natural fibres [8]. Before lamination, the fabrics were cut to the dimensions of 200 mm × 300 mm, then were conditioned at the constant temperature of 23 °C and 65 % relative humidity (RH) in a climate chamber for at least 24 hours before composite manufacturing [10, 19]. The resin was mixed with the hardener following the dosage indicated by the manufacturer (Mike Compositi-Mates, Italy), i.e. 100:26 by weight. For the fabric impregnation process, the recommendations provided by the resin manufacturer were followed. A square steel mould of the dimensions 300 mm × 300 mm ×10 mm was covered with ELA 20 μ detaching film used to prevent the resin from sticking to the metal plate, two plies of fabric were hand laid and impregnated manually with the epoxy resin. On top of it, a layer of Peel Ply PP105R100 fabric was placed (and then removed) to guarantee better elimination of air bubbles trapped in the fabric and improve the outflow of excess resin from the sample during the pressing phase. Lastly, a layer of ELA 20 μ release film was placed on the layer of Peel Ply. All the phases of the process are shown in Figure 2. Once the manual impregnation of the composites was completed, the composites were manufactured by cold moulding using a pressing machine (Metro Com 100 Comazzi, Novara Italy), under different configurations, without adding heat during the entire production process, reducing in this way energy consumption, at the expense of an increase in process times. The mould has an opening at the edges, which allows the excess resin to be removed. The dimensions of the composites are 200 mm × 300 mm × 2 mm.

Two series of composites (presented in Table 2) were manufactured regarding orientation of the hemp fabric to verify the bidirectional behaviour. The series was then divided into 4 groups (A, B, C, and D), which represented the different production methods employed for manufacturing the composite material; the variables used were the quantity of resin, the moulding load, and the duration of the applied pressure (as given in Table 3). In Table 3 the load/duration ratio expresses the load that the press transfers to the composite and the duration this load was applied.

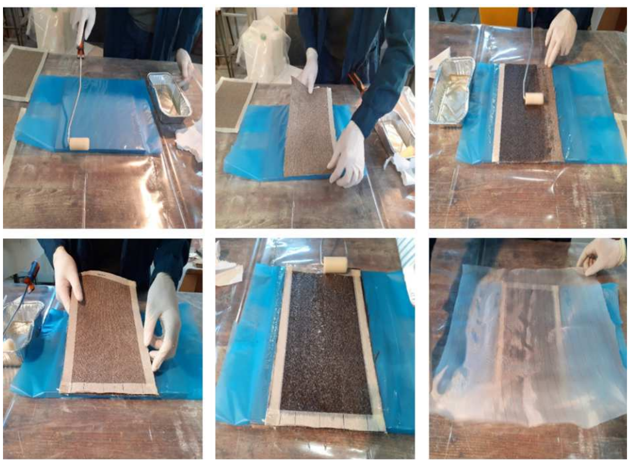

Fig. 2. Sequence of lamination phases

The moulding process carried out for the A, C and D group composites were similar. The composites in groups A and C were subjected to a load of 20,000 N, as in [10], while the group D composites were subjected to a load of 4000 N. After one hour the A, C and D group composite plates were loaded with 600 N for 5 hours. The composite plates in group B followed a different moulding process, then they were loaded for 6 hours with 600 N. All the processes were carried out at the ambient temperature of 25 °C.

TABLE 2. **Differences between the two series of produced composites**

Series	1	2
Characteristics	Two plies stacked with same orientation; weft direction parallel to test direction.	Two plies stacked orthogonal to each other.

TABLE 3. **Four groups of produced composites**

Group	Load /duration	Quantity of liquid resin [g] /fiber [g]*
A	20000 N/1 h + 600 N/5 h	200/100
B	600 N/6 h	200/100
C	20000 N/1 h + 600 N/5 h	300/100
D	4000 N/1 h + 600 N/5 h	200/100

*Amount of liquid matrix used during impregnation process is reported as ratio of mass of resin to mass of fibers, both expressed in grams.

Following manufacturing, the composite plates were conditioned at the constant temperature of 23 °C and 50 % RH, for at least four weeks to reach the moisture content equilibrium [10, 19]. After that period, all the composite plates were cut into five specimens that were used for the tensile tests, the dimensions of which were 250 mm × 25 mm × 2 mm according to ASTM D3039 [18].

Tensile tests

The tensile tests were conducted using a Galdabini press machine. This test permitted us to determine the tensile strength of the composites. To prevent failure in the anchoring, as suggested by ASTM D3039 [18], the extremity of the specimens was reinforced with tabs having a thickness of 1 mm at each side, the material of which was a carbon fibre composite. The dimensions of the tabs were 60 mm × 25 mm × 1 mm, compliant with the standard [18]. The tensile test was performed in displacement control at the speed of 2 mm/min as indicated by the standard [18]. Strain data acquisition was performed by means of digital image correlation (DIC) (see Fig. 3). The use of this technology requires preparation of the specimens to create a texture, thus the specimens were painted black, with a pattern of white dots. The specimens were kept in the machine and tensile forces were loaded until failure of the material. The elongation, breaking strength, ultimate tensile strength and Young's modulus of the composites were recorded.

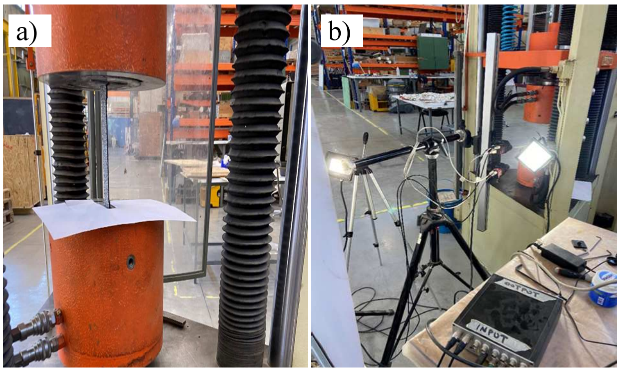

Fig. 3. Galdabini machine used for tensile test (a), digital image correlation instruments (b)

The data were statistically analysed by means of the ANOVA method (analysis of variance) to evaluate whether the means of the measured mechanical properties of the composite materials were significantly different from each other. For each test, the probability (*p*) was calculated, and the difference between the means is considered significant when the *p* is less than 0.05. The analysis was conducted utilizing Minitab v.18 software [20].

The microstructural analysis of the ruptured surface of the specimens after the tensile test was carried out using a scanning electron microscope (SEM).

RESULTS AND DISCUSSION

Hemp fabric and epoxy resin

Figure 4 shows the percentages by volume and weight of the constituents of the composites.

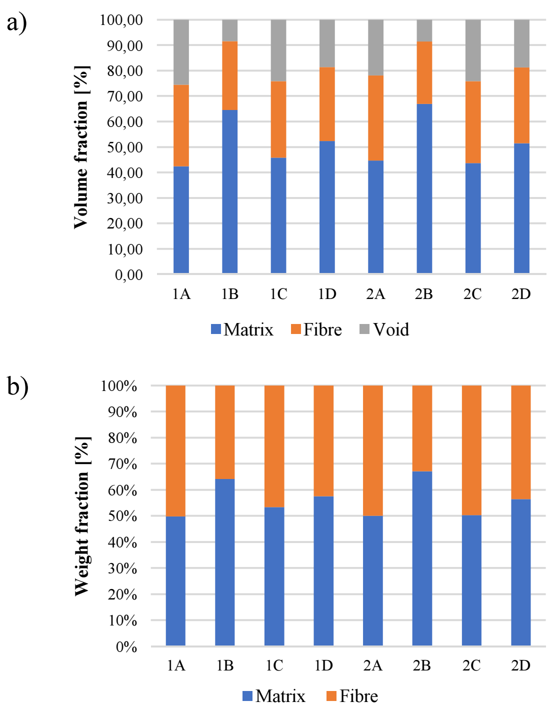

Fig. 4. Histograms of: a) volume percentage of matrix, fibres and voids, b) weight percentage matrix and fibre of all produced composites

It was observed that as the moulding load increases, there is a rise in the volume fractions of the fibers and voids, which go from 25 % and 10 % to 33 % and 24 %, respectively, and a simultaneous decrease in the volume fraction of the matrix, which goes from 65 % to 43 %. This is an indication of incorrect impregnation of the fibers by the resin due to its high viscosity caused by its use at room temperature.

The applied load is directly correlated with the volume of the voids and fibres present in the composite, and indirectly correlated with the volume of the matrix.

Tension test

The tension tests revealed elastic-brittle behaviour for all the different types of composites. Figure 5 displays the stress-strain curve of specimen 1A1, in which it is possible to see the elastic-brittle behaviour; the stress-strain curves for the other specimens will not be reported as they exhibit the same trend.

It is possible to observe a decrease in the stiffness of the material up to 0.5 % deformation, hence non-linear behaviour; after this value the material assumes linear behaviour up to brittle failure.

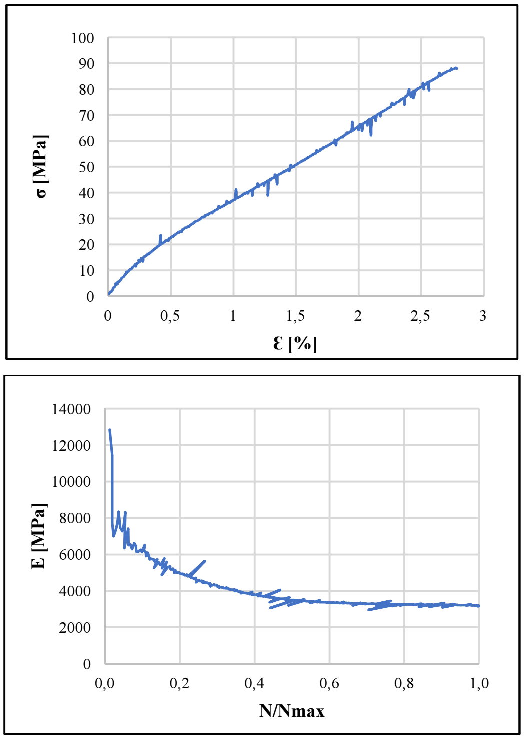

Fig. 5. Stress-strain in longitudinal direction for generic samples 1A1

Elastic module *E* shows a peak during the initial phase of loading, with values similar to the Young's modulus of the hemp fibres, and then a rapid decrease occurs till 0.1 N/N_{max}, where N is the tensile load applied to the specimens. The decrease continues less rapidly up to 0.6 of N/N_{max}; from this point *E* reached almost a constant value until failure.

The loss of stiffness between 0.1 and 0.6 of N/N_{max} is 50 % - 60 %, which is due to multiple factors:

1. Loss of adhesion between singular fibres and the matrix or between the yarns and the matrix as a consequence of poor adhesion between the two materials, a common problem of composites with natural fibres. Such phenomenon can be observed in the micrographs in Figure 6 obtained by SEM, where the fracture surfaces of specimens 1A1, 1B2, 2B4, 1C3 and 2C5 are shown. These specimens are representative of their composite type.
2. Fraying of the threads of the fabric caused by incorrect impregnation of the fabric, probably as a result of the cold moulding process, which proves the fact that the resin has high viscosity. Such phenomenon can be observed in Figures 7 and 6c where the micrographs of the fracture surfaces of specimens 1A2 and 1B2 obtained by SEM are presented. The micrographs highlight several strands of fibers that had flaked off and a reduction in the torsion angle with consequent elongation and loss of stiffness of the composite material.
3. The presence of voids in the composite. By means of SEM, it was observed that in the composites produced using higher pressure, such as the composites in groups A and C, the resin struggled to penetrate the reinforcement material, resulting in the presence of a few voids within the composite, as can be seen in Figures 6d and 7. On the other hand, the composites made employing a lower pressure, the group B specimens, have a high quantity of small voids as can be observed in Figure 8 and 6c. This could be due to the low compaction pressure during the forming phase of the material, as well as the lack of vacuum treatment of the composite.

a) b) c) d) e)

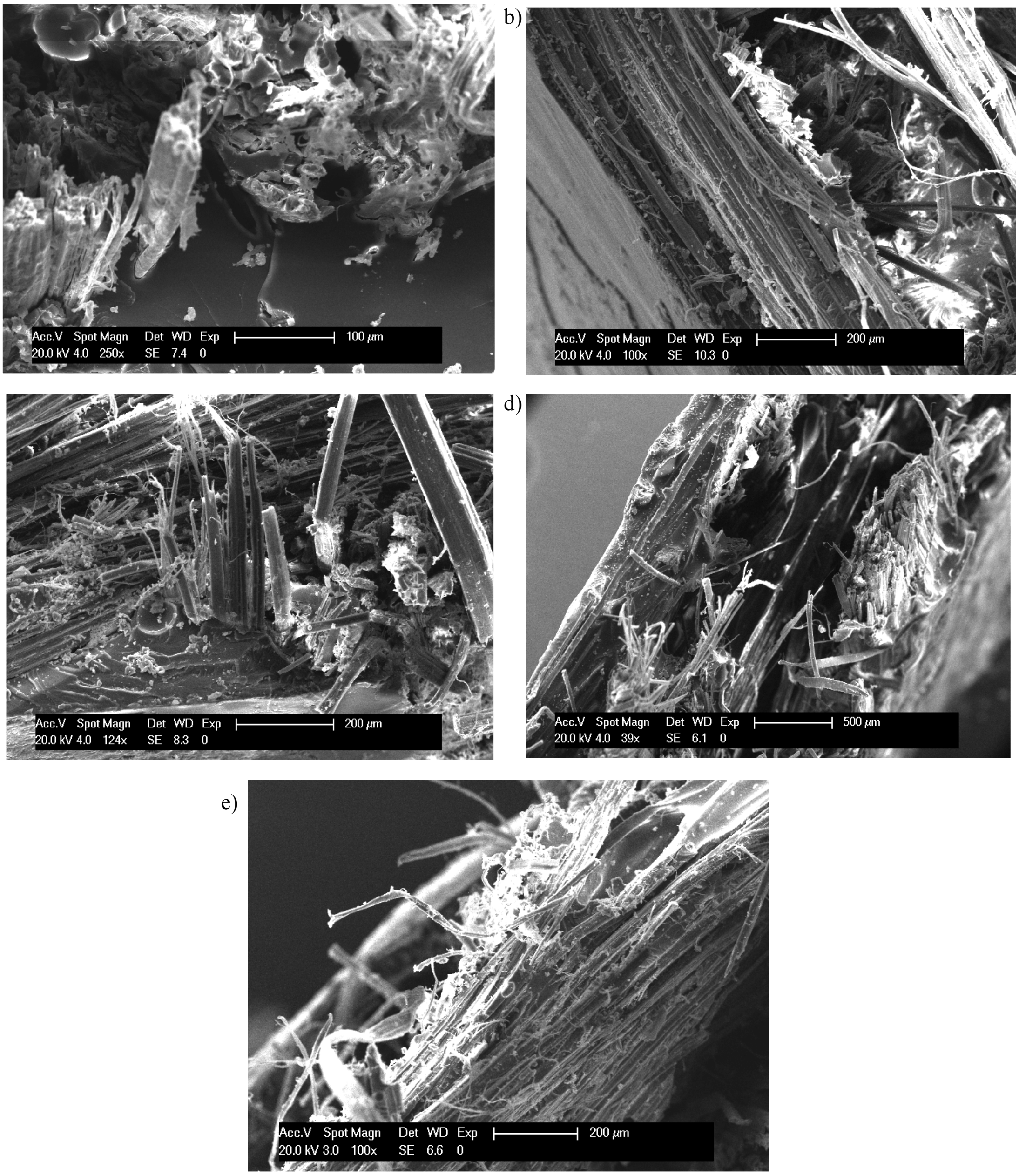

Fig. 6. Images obtained by SEM for fracture surfaces of some of specimens after tension test: a) specimen 1A1; b) specimen 1B2; c) specimen 2B4; d) specimen 1C3; e) specimen 2C5

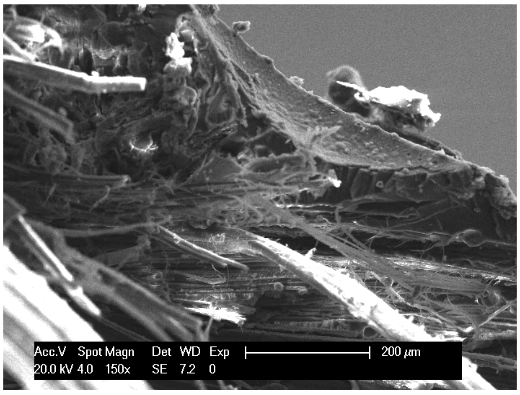

Fig. 7. SEM micrograph of fracture surface of 1A2 specimen after tension test

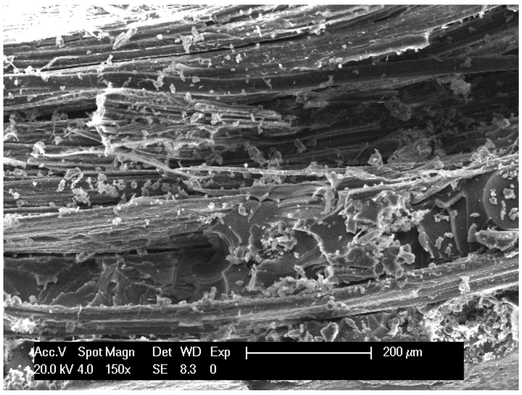

Fig. 8. SEM micrograph of fracture surface of 1B2 specimen after tension test

No significant differences were noted between Series 1 and Series 2 using SEM.

The density of the composites varies between 0.95 g/cm^3 - 1.15 g/cm^3; the group B specimens have the highest density, while the group A specimens exhibit the lowest density. Nonetheless, there is no difference in density between the two series, indicating that this value depends only on the manufacturing and lamination process of the composite as expected.

Table 4 displays the average and standard deviation of the mechanical properties of the different composite materials studied.

The groups of composites that exhibit the greatest longitudinal and transversal deformations are the ones with the highest percentage of voids, i.e. groups A and C, while the group B composites, which have the lowest percentage of voids, exhibit the lowest longitudinal and transversal deformations.

In terms of tensile strength, there do not appear to be significant differences between the groups. The Series 1 specimens exhibit lower tensile stress between 2 % and 8 % than those of Series 2; this is because the warp direction has a slightly higher density of 6.5 yarns/cm compared to that of the weft direction equal to 6.0 yarns/cm, which is caused by imperfect bidirectionality of the woven fabric. Since the Series 1 specimens have both layers of hemp fiber fabric oriented along the weft direction, they have slightly lower mechanical properties than those of Series 2, in which one of the layers is oriented along the warp direction.

Series 1 has an average transversal deformation value lower than that of Series 2 (from 13 % to 58 %), probably because of better meshing between the two layers of fabric.

Based on the obtained results, it was observed that the compaction pressure did not cause significant changes in the mechanical properties of the composite. For this reason, the composites belonging to group B are the ones that best meet the initial requirements, namely minimizing the environmental and economic impact of the production process, and consequently, of the final product, without significantly affecting its mechanical properties. The composites in group B have the same mechanical characteristics as the other composites, but require a lower compaction load during the production process, which means lower energy consumption, and in turn, lower economic and environmental costs.

TABLE 4. **Average and standard deviation of mechanical properties for all composites**

Specimen		Displacement	Force	ε_L	ε_T	σ	Poisson's ratio	E (0.1 N/Nmax)	E (0.6 N/N$_{max}$)
Series	Group	[mm]	[N]	[%]	[%]	[MPa]		[GPa]	[GPa]
1	A	3.98 (0.23)	3770.2 (199.5)	2.75 (0.12)	–0.64 (0.14)	86.63 (3.06)	0.23 (0.04)	6.040 (0.310)	3.345 (0.071)
	B	3.68 (0.17)	4554.7 (149.4)	2.54 (0.13)	–0.16 (0.02)	88.38 (2.82)	0.06 (0.01)	6.527 (0.854)	4.318 (0.523)
	C	3.96 (0.15)	3781.2 (93.3)	2.70 (0.28)	–0.23 (0.06)	81.21 (2.85)	0.08 (0.02)	4.846 (0.162)	3.314 (0.158)
	D	3.66 (0.11)	3871.3 (109.1)	2.55 (0.05)	–0.28 (0.03)	80.31 (3.89)	0.11 (0.01)	7.180 (0.443)	3.662 (0.157)
2	A	3.69 (0.19)	3671.6 (122.0)	2.72 (0.12)	–0.74 (0.09)	88.49 (3.72)	0.27 (0.03)	7.234 (0.322)	3.700 (0.178)
	B	3.42 (0.21)	4269.1 (188.3)	2.51 (0.12)	–0.37 (0.09)	75.16 (3.38)	0.15 (0.03)	5.587 (0.348)	3.812 (0.111)
	C	3.62 (0.12)	3813.3 (104.4)	2.49 (0.07)	–0.55 (0.05)	88.45 (1.70)	0.22 (0.02)	7.181 (0.185)	3.880 (0.098)
	D	3.67 (0.06)	3953.4 (95.9)	2.51 (0.07)	–0.46 (0.05)	84.29 (0.86)	0.18 (0.02)	6.539 (0.724)	3.867 (0.123)

To better understand the data reported in Table 4, box plots are given in Figure 9 for all the types of composites for the main mechanical properties: σ, Poisson's ratio, E at 0.1 N/N_{max} and E at 0.6 N/N_{max}. In each box, the red line is set at the median value, while the bottom and top edges of the box indicate, respectively, the 25th and 75th percentiles; black broken lines extend to the most extreme data points, which are not considered outliers, while the outliers are plotted individually using a red cross marker (Fig. 9c and d).

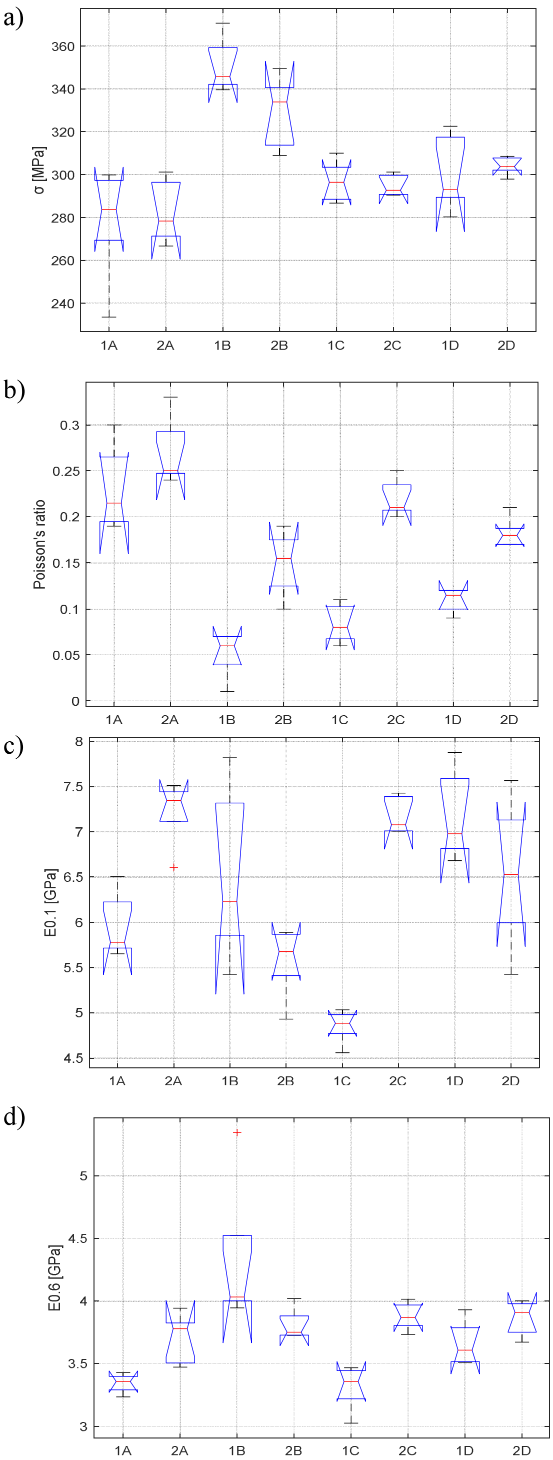

Fig. 9. Box plots of mechanical properties for all tested species: a) tensile strength σ; b) Poisson's ratio; c) elastic modulus for 0.1 N/N_{max}; d) elastic modulus for 0.6 N/N_{max}.

The box plots in Figure 9a, show that for groups A and C (groups characterized by high forming pressure), the specimens from Series 2 exhibit higher $E_{0.1}$ values compared to those from Series 1. Conversely, for the specimens from groups B and D, where the compaction pressure during forming was low, the opposite trend is observed.

Statistical analysis

As can be seen from Table 6, there is no statistically significant variation in the tensile strength of the material between the two series. Regarding the groups, the only one whose specimens show statistically significant differences compared to the others is group B, with its tensile strength values being higher than the others.

In Table 7, it is evident that there is a difference between the specimens of Series 1 and those of Series 2, except those belonging to group A. Specifically, the specimens from Series 2 exhibit higher Poisson ratios than those from Series 1. This means that the specimens from Series 2 undergo greater transverse deformations compared to those from Series 1, given the same longitudinal deformation. Additionally, group A has a p-value lower than 0.05 compared to the other groups, indicating that the specimens from this group exhibit greater deformation.

Tables 8 and 9 do not show a clear difference among the groups in terms of Young's modulus.

TABLE 6. ***p*-values for σ. Values lower than 0.05 are indicated in bold**

	2A	1B	2B	1C	2C	1D	2D
1A	1.000	**0.000**	**0.000**	0.585	0.704	0.326	0.172
2A		**0.000**	**0.001**	0.819	0.901	0.561	0.344
1B			0.328	**0.000**	**0.000**	**0.000**	**0.001**
2B				**0.033**	**0.021**	0.090	0.188
1C					1.000	1.000	0.992
2C						0.998	0.973
1D							1.000

TABLE 7. ***p*-values for Poisson's ratio. Values lower than 0.05 are indicated in bold**

	2A	1B	2B	1C	2C	1D	2D
1A	0.467	**0.000**	**0.011**	**0.000**	0.999	**0.000**	0.251
2A		**0.003**	**0.000**	**0.000**	0.156	**0.000**	**0.001**
1B			**0.001**	0.662	**0.000**	0.094	**0.000**
2B				**0.038**	**0.023**	0.532	0.722
1C					**0.000**	0.878	**0.000**
2C						**0.000**	0.457
1D							**0.018**

TABLE 8. **p-values for $E_{0.1}$. Values lower than 0.05 are indicated in bold**

	2A	1B	2B	1C	2C	1D	2D
1A	0.014	0.708	0.950	**0.047**	**0.021**	**0.021**	0.686
2A		0.444	**0.001**	**0.000**	1.000	1.000	0.465
1B			0.137	**0.001**	0.542	0.544	1.000
2B				0.403	**0.001**	**0.001**	0.128
1C					**0.000**	**0.000**	**0.001**
2C						1.000	0.564
1D							0.566

TABLE 9. **p-values for $E_{0.6}$. Values lower than 0.05 are indicated in bold**

	2A	1B	2B	1C	2C	1D	2D
1A	0.441	**0.000**	0.143	1.000	0.061	0.580	**0.073**
2A		**0.011**	0.996	0.271	0.945	1.000	0.963
1B			0.060	**0.000**	0.149	**0.006**	0.126
2B				0.067	1.000	0.979	1.000
1C					**0.025**	0.394	**0.030**
2C						0.866	1.000
1D							0.899

Comparison with similar composite materials from literature

Table 10 shows the fiber and resin used, the manufacturing process, the tensile strength and elastic modulus of different composites produced in other studies found in the literature, as well as the data of the Series 1 Group B composite, chosen as a representative of all the composites manufactured in the current study.

There are few papers in which the manufacturing process is like the one in the present research, i.e. without heat transfer in the press mould. Sivasankar et al. [22] fabricated a composite consisting of 50% hemp fiber and 50 % Abaca fiber in the form of a unidirectional fabric, and an epoxy resin. The composite was made using a hand rolling and cold moulding process; the tensile tests showed an average composite tensile strength of 48.5 MPa. Shebaz Ahmed et al. [23] produced a composite of hemp and flax fiber in the form of a unidirectional fabric with an epoxy matrix, whose tensile strength was found to be equal to 46.1 MPa. In both cases, the tensile strength values associated with the fibre-reinforced composites are lower than those obtained in this research.

Higher values of tensile strength can be obtained with the hot moulding process. In the research of Corbin et al. [10], hemp fiber and epoxy resins were hot moulded at 130 °C at the pressure of 3 bar for 1 h. This process guarantees complete impregnation of the hemp fiber fabric due to the fluidity of the resin as confirmed by the low value of voids, i.e. 0.5 vol.% - 3 vol.%, much lower than the percentage of voids found in this paper. The tensile strength of the composite in [10] was equal to 100 MPa for the direction parallel to the warp and 200 MPa for that parallel to the weft, while Young's modulus was equal to 12 GPa along the warp and 16 GPa along the weft direction. Lower mechanical properties are obtained when natural adhesives like PLA [14, 24] and cashew nutshell liquid are used, owing to the lower mechanical properties of the resin itself. The design of the mechanical properties should depend on the field of application of the material.

TABLE 10. **Values of tensile strength and Young's modulus for composites manufactured in different studies found in literature and data on Series 1 group B composite manufactured in this research**

Authors	Fiber	Matrix	Production process	Tensile strength [MPa]	Young's modulus E [MPa]
Specimen 1B	Hemp fiber bi-directional fabric	Epoxy resin	Cold moulding	88	4318
[22]	Unidirectional, abaca and hemp fiber	Epoxy resin	Cold moulding	49	–
[23]	Unidirectional woven fabric of hemp and flax fiber	Epoxy resin	Cold moulding	46	–
[10]	Hemp unidirectional woven fabric	Epoxy resin	Hot moulding at 130 °C	90-210	11000-20000
[14]	Non-woven hemp fiber	PLA	Hot moulding at 170 °C	41	5600
[24]	Short hemp fiber	Polypropylene	Hot moulding at 200 °C	25	–
[13]	Non-woven fiber hemp	Cashew nutshell liquid	Moulding	29	7200

CONCLUSIONS

This research presents the mechanical properties of composite materials reinforced with bidirectional hemp woven fabric made using a very easy production process without any heat treatment.

The following conclusions can be drawn:

- The value of Young's modulus at 0.6 N/N_{max} until failure varies between 3.3 and 4.4 GPa. This value is 8 % to 30 % higher than the E value of the epoxy resin; the growth is due to the presence of the hemp fiber reinforcement in the composite, which thus increases in this way the mechanical properties of the resin alone.
- The presence of the hemp fibres raised the maximum tensile stress of the matrix by 23 % - 64 %, depending on the group of produced composites.
- The groups of composites that exhibited the highest longitudinal and transversal deformations are the ones with the highest percentage of voids, i.e. group A and group C, while group B, the composites with the lowest percentage of voids, have the smaller longitu-

dinal and transverse deformations; this correlates with the high value of stiffness of the group B composites than those of groups A and C.

- It was observed that as the press load increases, there is an increment in the percentage (by volume) of fibres and voids and a simultaneous decrease in the percentage (by volume) of the matrix, an indication of low impregnation of the fibres by the matrix, as observed in Figures 6c and 7, in which it is possible to see the fabric less impregnated compared with the fabric of the composite displayed in Figure 8. This can be due to the high viscosity of the resin caused by the production process in which there was no heat transfer. Owing to the high viscosity of the resin, optimal impregnation of the woven fabric did not occur, trapping air bubbles inside it during manufacturing, which were impossible to eliminate even using high pressure during the moulding process. The increment in the pressure led only to a reduction in resin present in the composite, but there was no reduction in the void volume. This is because the resin is unable to penetrate the internal layers of the fabric, which remained present exclusively on the external part of the fabric, impregnating only the external fibers of it and not the internal ones. This causes the resin to create an external surface that prevents the air bubbles from escaping from the fabric even if it is subjected to high pressure. This applies to both the level of the fabric as a whole and at the level of the fiber bundles that make up the fabric itself, in which only the external fibers of the bundle were impregnated by the resin, while the internal fibers of the bundle were not impregnated.
- The tensile strength of the composites was found to be independent of the press load. This depends in part on the considerations seen in the previous point and on the conducted lamination process. A hand lamination process was used, not followed by any type of vacuum or special autoclave treatment at high temperatures. These processes would have guaranteed a greater reduction in the volume of voids and matrix present in the composite.

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