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Mechanical properties of boards made in biocomposites reinforced with wood and Posidonia oceanica fibers

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Abstract

The development of biocomposites has valorized some natural products related to natural processes or crop industries. In this regard, Posidonia oceanica is a marine phanerogam typical of Mediterranean coasts, in which due to tourism industry a lot of resources are destined to remove and treat Posidonia residues left on beaches. In this work an alternative to recycle this natural waste has been studied. Biocomposites with Posidonia and pine-wood particles were tested as an alternative to structural wood particle boards used in construction. Different substitution ratios (pine by Posidonia) were prepared in two different polymeric matrices and their mechanical properties were tested. Particles boards made in 75% Posidonia oceanica and 25% wood particles and a MDI matrix (20 to 30% by fibers mass) showed the best strength and stiffness to density ratios. This stiffness was even similar to a panel made totally in wood and MDI in the same dosage, i.e. 75% of pine fibers could be replaced by Posidonia with low stiffness loss.

Keywords: Biocomposites, Posidonia oceanica, Recycling, Mechanical properties, Structural boards.

1. Introduction

The use of natural or synthetic fibers is a traditional technique to improve the mechanical behavior of brittle materials [1-2]. Altohough in the last years a vast scientific production has been performed related to green composites or biocomposites that use natural fibers [2-6], with applications in all engineering fields [4,7]. Among the natural admixtures pineapple leaves [8], bamboo [9], olive seeds flour [10] can be quoted. Generally, these works aim to reuse a natural waste which in most cases can improve the properties of a polymer [2-4] or cement composite [11-12], or even replace other less sustainable fibers typically used with this purpose, such as glass [13], carbon [14] or hybrid fibers [15].

Posidonia oceanica is a type of marine phanerogam found on both the Atlantic and the Mediterranean coasts [16]. In the latter, the extensive meadows of Posidonia oceanica (PO) are vital to the marine ecosysthem, are a good indicator of water quality [17], and have been used as a parameter for beach clasiffication [18]. The Balearic Islands and Almería show the most extensive meadows with greater leaf density in the Mediterrenean coast of Spain [19]. However, these plants lose a high amount of leafs that are transported to the coast and aqumulate on beaches. This spontaneous acumulation requires a specific waste disposal with negative consecuences to beach qualities, specially in turistic areas such Spain or Tunicia [20]. Besides, further usage as energy source is difficult due to its low combustible behavior under fire [21]. Therefore, the valorization of Posidonia oceanica as a reinforcement in composites would serve both for mechanical and waste recycling purposes.

Regarding the reuse of PO as a component in biocomposites [21-23], Posidonia boards in a polymer matrix were patented by Ferrazzini in 1985 due to their good behavior under fire [21]. This fire resistance, very important in biocomposites [24-25], was also reported in cement composites reinforced with PO fibers [17], where the material did not burn under any fire exposure conditions. Recently, another approach to PO recycling has appeared to developed nanocomposites based on cellullose nanocrystals obtained from PO treatment [26].

The actual exploitation of wood resources is another issue to be addressed nowadays. Forest overexploitation in some parts of the world has led to alternative ways of manufacturing particles boards, in which some part or even all wood materials should be replaced [27]. Thereby Posidonia oceanica can emerge as a suitable addition on its own for particle boards, or as a mixed Posidonia-wood material.

The use of recycled Posidonia oceanica as a building material would reduce significantly the costs of waste disposal operations of this natural residue, while enhancing their composites due to its lightness and fireproof properties. This combination makes PO suitable as addition to polymer matrices for interior lining constructive elements, e.g. flooring systems or panels, with mechanical and fire requirements.

This research is aimed at the mechanical behavior of mixed Posidonia oceanica and pine wood particle boards, which will be used for structural purposes, whether in architecture or in the field of furniture design. This objective is focused at the improvement of wood particles boards as FP (obtained by heat and pressure), trying to offer a more sustainable linning alternative by means of recycling a natural waste material (Posidonia). Therefore the effect of the polymer matrix type or the relative fibers proportions will be addressed to optimize the mechanical behavior of these biocomposites. Moreover, the Posidonia oceanica, used as addition particles, can reduce costs and enhance the thermal stability and fire resistance of the composites.

2. Experimental procedure

2.1. Materials and dosages

In this study polymer composites reinforced with natural fibers were tested. Two different fibers were used, wood particles (*Pinus Pinaster*) and *Posidonia oceanica*. The objective of this research aims at the reduction of wood content in particle boards, therefore pine particles are replaced by increasing amounts of Posidonia fibers, even total replacement was reached to test if PO fibers alone can achieve suitable mechanical properties. For each PO substitution the mechanical performance of particle boards was assessed.

The Posidonia oceanica used in this investigation has been obtained directly from natural deposits accumulated on the beaches of Alicante (Spain). Prior to being used as addition in polymer composites, the material as collected should go through several preliminary treatments: cleaning, drying, crushing and sieving. Fig. 1 includes photographs taken during the different parts of the PO collection and preprocessing.

First, for the cleaning process, all PO was submerged in fresh water to remove salt particles and other organic and inorganic debris, which were also manually removed. Afterwards, the clean PO was dried 2 hours at 110 °C in an electric oven. Once the material was clean and dried, it was crushed mechanically to a 1 mm maximum particle size using a cutting mill, supplied by Retsch. And finally the PO was sieved to remove all particles lower than 0.3 mm. this last treatment is necessary to optimize the particle-resin mixing process, because due to their large specific surface area they would absorb most of the polymer and the mixture wouldn't be homogeneous.

Two different polyurethane polymer matrices were used, PU-823 and PU-815 supplied by Kefren Adhesivos. PU-823 (PU) is a monocomponent PU and PU-815 (MDI) is a bicomponent PU, which contains MDI isocyanates. After all the pretreatments were performed, and PO has been prepared, the resin was poured into the wood-Posidonia mixture and the mix was stirred by hand until a homogeneous consistency was achieved. Afterwards, the composite was poured into 250x250x120 mm steel molds in layers of 10 mm thick or lower. Once all the material has been poured, samples were taken to a mechanic press to apply pressure during resin curing process. This pressure was maintained for 2 to 6 hours (the specific conditions for each dosage are summarized in Table 1 and Table 2). Afterwards each panel was demolded and samples were prepared and kept at room conditions (20 ºC and 65% RH) until testing.

Specimen's dimensions agree with the prescriptions for wood panels included in EN 789:2004 [28]. In abcense of a more specific standard for PO, the current research is based on wood boards testing conditions. Therefore, for compressive tests, samples were prepared according to EN 789:2004 [28], depending on the final thickness of each panel the dimensions and number of layers for mechanical testing specimens was adjusted to fulfill slenderness conditions. The length of all samples was between 210 and 240 mm, the initial dimensions of each panel was a bit higher (250 mm), but all edges were cut to ensure a uniform curing pressure application in the test specimens. If board thickness was lower than 40 mm, several layers should be attached together to increase the total thickness, i.e. two layers for thickness between 15 and 40 mm, and four layers between 10 and 14. Then specimen's width should be reduce accordingly.

Different relative dosages of PO and wood (W) fibers were used, i.e. PO/W mass ratios were fixed at 0/1 (only wood particles), 3/1, 1/1, 1/3 and 1/0 (only Posidonia). Polymer dosages varied from 10% to 60% with respect to total fibers mass (PO+W). Table 1 and Table 2 include all details for each dosage prepared for PU and MDI resins, respectively. The series reinforced with only PO fibers were used to study the influence of other variables, such as the curing time or stress. In this case all time-stress combinations didn't guarantee the physical stability of the composite, either the time or stress were too short or too low, or the resin amount wasn't enough to conglomerate all fibers in the composite. Thereby in these cases there won't be any mechanical strengths, as will be discussed later.

2.2. Mechanical testing.

For each dosage mechanical tests were performed according to EN 789:2004 [28], which comprised density measures, compressive strength tests and elastic modulus upon compression assessment. Compressive tests were made under load control conditions as specified in EN 789:2004 [28]. Longitudinal strains were registered with two strain gages located on opposite sides of each specimen. Load and strain values were registered until materials failure, and afterwards, both compressive strength (f_c) and elastic modulus (E_c) were assessed using Eq. (1) and Eq. (2) respectively.

$$f_c = \frac{F_{max}}{A} \tag{1}$$

$$E_c = \frac{F_2 - F_1}{A \cdot (\varepsilon_2 - \varepsilon_1)} \tag{2}$$

Where F_{max} is the maximum load value registered during the test; A is the cross section of each specimen; F_1 and F_2 are the load values corresponding to $0.1F_{max}$ and $0.4F_{max}$ respectively; ε_1 and ε_2 are the strain values for these load levels.

3. Results and discussion

First, all dosages prepared, as shown in tables 1 and 2, weren't suitable for testing, hence some recommendations regarding the curing conditions should be mentioned. The manufacturing pressures must be greater than 2 MPa, otherwise it is not possible to obtain material densities with structural performance. If lower pressures were applied, the resulting composite wasn't cohesive enough, regardless how long the curing under pressure lasted. For example, a specimen submitted only to 1.25 MPa wasn't cured appropriately, hence the composite was too soft and broke during post-manufacturing. Another problem that should be taken into account is the PU dosage. If an excess of PU resin was used (60% by fiber mass), the samples weren't neither suitable for testing, because the resin couldn't hardened properly.

Table 3 summarizes all mechanical properties results measured for the PU biocomposites, for all the Posidonia and wood relative dosages, while the MDI composites counterparts are included in Table 4. For a preliminary analysis no differentiation between fiber compositions has been made, and all results only distinguishing matrix type are represented in Fig. 2. All graphs include linear functions obtained by regression analyses, both function equations and Pearson R^2 coefficients are also included in each case. The effect of polymer dosage on the composite's density is represented in Fig. 2(a). As a general rule, higher densities were achieved as the amount of resin was increased. However, the fact of not considering different series for each

PO/W dosage led to poor linear regressions, as shown in the low R^2 coefficient values. Therefore further analyses should be made later taken into account this factor. Fig. 2(b) includes compressive strength evolution for increasing polymer dosages. The same increasing trend can be observed, but if the matrix is PU an excessive dosage can reduce the composite's strength. Despite the apparent result dispersion, the correlation between strength and resin dosage is stronger (R^2>0.5), even if fiber characteristics are ignored. Fig. 2(c) includes the same analysis for elastic modulus, which once again show a similar ascending trend as polymer dosage is increased. Nonetheless, the dispersion is much higher in this case, because the particular fiber proportion can't be ignored here. The relative proportion of wood and Posidonia can affect the mix workability, thus obtaining very different elastic modulus for the same resin dosage and diverse fiber mixture. Furthermore, the stiffness of the MDI polymer is higher than PU, therefore their composites should follow the same pattern.

As a summary of this first analysis, Fig. 3 shows the relationship between each mechanical property and the other two. In all these cases, regardless the resin type (PU or MDI), a dosage increase meant higher mechanical properties (density, strength and stiffness). Second, for the same strength level, MDI composites were stiffer, i.e. their elastic modulus were higher. And third, a composite with the same density showed higher strength for PU composites, but higher elastic modulus if MDI was used.

After this first analysis, the influence of the relative fiber dosage, i.e. Posidonia/wood ratio, on the mechanical properties is discussed. For this purpose, Fig. 4 and Fig 5 include the average mechanical properties for each different PO/W ratio and matrix type, PU or MDI. Fig. 4(a) shows the densities of PU composites with different PO contents. Besides the general trend that higher resin dosage equals higher density, PO fibers had the same effect, i.e. the higher the PO dosage was the higher composite's density was. Therefore, the densest composites were those with only Posidonia, while the less dense contained only pine wood particles. On the other hand, Fig. 4(b) includes the average densities of MDI samples for each PO/W ratio, and the trend is similar than for PU mixes, i.e. higher density was obtained for higher resin dosage. However, the density increase was smaller for each specific PO/W ratio. Besides, an excess in the resin amount meant a density decrease. And as the PO addition increased, also density did, with the exception of the specimens with only Posidonia, which showed the lowest densities.

Fig. 5 includes the average value of specific compressive strength and elastic modulus, i.e. the ratio between the material's strength and modulus with respect to its density. Fig. 5(a) include the specific strength for the PU composites, which also presented an increasing tendency as the resin amount increased. In this case, the samples prepared only with PO fibers showed the highest strength. It is worth noticing that an excessive PU amount, beyond 40%, led to a strength loss, or even to an unusable composite (e.g. 75%wood particles with 60% PU dosage). An analogue discussion may be done for the MDI composites. A similar tendency was observed for the compressive specific strength, Fig. 5(b). The material strength increased for higher resin amounts. All samples that combine both fibers had similar strength, if at least a 20% (by fiber mass) resin dosage was used. However, dosages with only one type of fiber showed very different behavior. Specimens made only with PO and MDI were the weakest, while their W counterparts were the strongest. Compared with PU composites, MDI composites didn't show a strength loss related to resin excess, although MDI amounts were lower than PU.

Finally, Fig. 5(c) and 5(d) include average values for specific elastic modulus of PU and MDI composites, respectively. In this case MDI specific moduli were higher than their PU counterparts. Increases in PU dosage, Fig. 5(c), didn't guarantee higher specific modulus, despite the elastic modulus could be higher (Table 3) the material was also denser, and hence the specific property wasn't improved. On the other hand, MDI composites showed high specific stiffness, even for higher PO substitution, e.g. 75%PO samples had almost the same stiffness than composites made only in wood particles.

To sum up, PU composite's mechanical behavior was better if only Posidonia was used, while MDI resin showed higher strength with only wood particles. If a mixture of both additions was used there weren't big strength differences between both matrices, but MDI composites were stiffer than their PU counterparts. Table 5 includes the minimum mechanical properties for particle boards for structural applications in dry environment, as shown in Spanish and European Standards [29]. For the PO composites of this research, higher density is required (between 0.9 and 1.0 g/cm^3) in order to obtain compressive strength or elastic modulus closer to the standard particle boards. Therefore, the application of this material directly as a conventional particle board is not directly recommended from a structural point of view. However, in some situations with lower mechanical performance requirements, these biocomposites could be used, especially if the sustainability component is evaluated [30], as these panels reuse a natural waste product.

One final discussion should be made related to the failure process of each sample, which can be important for design recommendations if structural performance is necessary. Depending on the dosage, and ergo their mechanical strength, three different types of failure have been distinguished, as shown in Fig. 6. In order to quantify this phenomena, Fig 7 includes the frequencies (absolute and relative for each dosage) of each failure mode for each resin and PO/W ratio. The first mode, Fig. 6(a), is characterized by the failure of one support, and is typical of soft composites, such those made only in PO (Fig. 7). Thus, board panels made in these dosages may have problems related to connections and anchorages, besides their strength was usually low. Fig. 6(b) illustrates the samples that fully developed their mechanical strength, and all layers failed simultaneously near their middle sections. All samples made exclusively in wood and MDI showed this type of failure, Fig. 7(b). The third mode comprises buckling failures, Fig. 6(c), therefore samples failed before reaching their real maximum strength. MDI composites showed predominantly this failure, hence if their thickness is adjusted this composites could achieve even higher strengths. In that case, mixed Posidonia and wood particles composites could be used with structural purposes. On the other hand, PU composites failed either because strength (type 2) or buckling (type 3).

The cost per unit area of panels made in pressed Posidonia polymer composites is higher than the cost of similar solutions made in wood particles boards. This extra cost is mainly due to all Posidonia preprocesing costs, i.e. collection, cleaning, drying, grinding and sieving. However, this difference is compensated by the reduction of environmental cost related to natural resources. Moreover, the cost of beach maintenance and cleaning is reduced because the revalorization of a waste like Posidonia. Finally, for future research and in order to optimize this sustainability factor, other type of natural binders may be used, such as palm tree oil [31-32], tree bark extract [33], castor stem [34], liquefied wood [35-37], mimosa bark extract [38], or liquefied bamboo [39].

4. Conclusions

Different biocomposites were prepared with a mixture of Posidonia oceanica and pine wood particles in two different polyurethane matrices, in order to assess their possible use as structural panels. After all mechanical testing and its analysis, the following conclussions can be drawn.

As a general trend, higher dosages of resin increased all mechanical properties (density, compressive strength and elastic modulus), regardless the resin type. MDI composites were stiffer (higher elastic modulus) for the same level of strength or density. Hence, this resin would be more appropriate if structural applications were desired.

Posidonia fibers worked better with PU resin, while wood particles did with MDI, i.e. PU composites with 100% Posidonia and MDI composites with 100% pine particles showed higher strengths than their mixed PO/W counterparts did. In order to guarantee a proper elastic modulus some wood addition was desirable. In addition, MDI adhesive improved compressive strength when mixing both fibers.

In comparison with standard wood particle boards, the mechanical performance of mixed Posidonia and wood boards does not reach normative requirements (as included in European standards). Due to the higher density of PO fibers than pine particles, higher board density is necessary to achieve strength and modulus close to commercial pannels. Nonetheless, the reuse of a natural waste product should be taken into account for more sustainable composites, despite the mechanical properties loss.

As a compromise between material's specific mechanical properties and environmental cost, particles boards made in 75% Posidonia oceanica and 25% wood particles and a MDI matrix (20 to 30% by fibers mass) showed the best strength and stiffness to density ratios. This stiffness was even similar to a panel made totally in wood and MDI in the same dosage.

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Tables

Table 1. Dosages and curing conditions for mixed wood and Posidonia PU composites.

PO/W (mass% PO/W)	*Resin type*	*Resin dosage* (by fiber mass PO+W)	p_{curing} (MPa)	t_{curing} (h)	t_1 (mm)
100%W	PU	10%	3.75	6	13
100%W	PU	20%	3.75	6	13
100%W	PU	30%	3.75	6	13
25%PO + 75%W	PU	15%	3.75	6	11-13
25%PO + 75%W	PU	20%	3.75	6	11-15
25%PO + 75%W	PU	30%	3.75	6	11-14
25%PO + 75%W	PU	40%	3.75	6	11-15
25%PO + 75%W	PU	50%	3.75	6	12-15
50%PO + 50%W	PU	15%	3.75	6	11-13
50%PO + 50%W	PU	20%	3.75	6	12-14
50%PO + 50%W	PU	30%	3.75	6	11-15
50%PO + 50%W	PU	40%	3.75	6	11-13
50%PO + 50%W	PU	50%	3.75	6	10-15
75%PO + 25%W	PU	15%	3.75	6	10-15
75%PO + 25%W	PU	20%	3.75	6	10-14
75%PO + 25%W	PU	30%	3.75	6	10-14
75%PO + 25%W	PU	40%	3.75	6	10-14
75%PO + 25%W	PU	50%	3.75	6	10-15
100%PO	PU	15%	2.5	6	-
100%PO	PU	20%	2.5	6	25
100%PO	PU	30%	2.5	6	24
100%PO	PU	40%	2.5	6	15
100%PO	PU	60%	4	6	16

* p_{curing} and t_{curing} refer to the curing conditions, i.e. pressure value and duration; t_1 board thickness.

Table 2. Dosages and curing conditions for mixed wood and Posidonia MDI composites.

PO/W (mass% PO/W)	*Resin type*	*Resin dosage* (by fiber mass PO+W)	σ_{curing} (MPa)	t_{curing} (h)	t_1 (mm)
100%W	MDI	20%	4	3	14
100%W	MDI	30%	4	3	13-14
100%W	MDI	40%	4	3	14
25%PO + 75%W	MDI	15%	4	3	11-12
25%PO + 75%W	MDI	20%	4	3	12
25%PO + 75%W	MDI	30%	4	3	12
25%PO + 75%W	MDI	60%	1.25	3	17-18
50%PO + 50%W	MDI	15%	4	3	11-12
50%PO + 50%W	MDI	20%	4	3	11
50%PO + 50%W	MDI	30%	4	3	11-12
75%PO + 25%W	MDI	15%	4	3	10-11
75%PO + 25%W	MDI	20%	4	3	11
75%PO + 25%W	MDI	30%	4	3	11
100%PO	MDI	10%	3	2-3	13
100%PO	MDI	15%	2.5-5	3	17-26
100%PO	MDI	20%	2-2.5	3-6	14-30
100%PO	MDI	25%	3	2-3	15-18
100%PO	MDI	30%	2-2.5-4	3	11-21
100%PO	MDI	40%	1.25	3	15

* p_{curing} and t_{curing} refer to the curing conditions, i.e. pressure value and duration; t_1 board thickness.

Table 3. Mechanical properties average values for mixed wood and Posidonia PU composites.

Resin dosage (by fiber mass)	*Fibers* (%PO/%W)	σ_{curing} (MPa)	t_{curing} (h)	*Density* (g/cm^3)	f_c (MPa)	E_c (MPa)
PU 15%	100/0	2.5	6	0.790	7.46	352.9
PU 20%	100/0	2	12	0.990	6.11	456.3
PU 30%	100/0	2.5	12	0.830	7.39	346.1
PU 60%	100/0	4	6	1.110	9.45	361.8
PU 15%	75/25	3.75	6	0.825	2.08	461.6
PU 20%	75/25	3.75	6	0.878	2.89	668.3
PU 30%	75/25	3.75	6	0.951	3.30	726.1
PU 40%	75/25	3.75	6	1.019	5.71	582.5
PU 50%	75/25	3.75	6	1.049	5.21	543.6
PU 15%	50/50	3.75	6	0.858	2.92	595.5
PU 20%	50/50	3.75	6	0.793	3.69	669.1
PU 30%	50/50	3.75	6	0.877	3.93	542.7
PU 40%	50/50	3.75	6	0.990	6.71	896.7
PU 50%	50/50	3.75	6	1.054	4.38	535.4
PU 15%	25/75	3.75	6	0.831	2.01	516.9
PU 20%	25/75	3.75	6	0.814	3.47	588.9
PU 30%	25/75	3.75	6	0.900	4.06	795.5
PU 40%	25/75	3.75	6	0.954	6.32	849.8
PU 50%	25/75	3.75	6	0.955	6.56	814.5
PU 10%	0/100	3.75	6	0.734	2.63	527.5
PU 20%	0/100	3.75	6	0.795	2.59	409.9
PU 30%	0/100	3.75	6	0.848	3.96	528.8

Table 4. Mechanical properties average values for mixed wood and Posidonia MDI composites.

Resin dosage (by fiber mass)	*Fibers* (%PO/%W)	σ_{curing} (MPa)	t_{curing} (h)	*Density* (g/cm^3)	f_c (MPa)	E_c (MPa)
MDI 10%	100/0	3	3	0.633	0.99	308.1
MDI 15%	100/0	2.5	3	0.629	1.16	346.0
MDI 20%	100/0	2	6	0.698	1.73	392.2
MDI 20%	100/0	2	3	0.663	1.66	416.3
MDI 20%	100/0	2.5	3	0.872	2.21	577.6
MDI 25%	100/0	3	3	0.823	3.16	497.3
MDI 30%	100/0	2	3	0.797	2.44	409.4
MDI 30%	100/0	2.5	3	0.761	1.40	397.2
MDI 30%	100/0	4	3	0.996	3.24	620.1
MDI 15%	75/25	4	3	0.949	1.62	522.5
MDI 20%	75/25	4	3	0.930	3.88	893.0
MDI 30%	75/25	4	3	0.992	4.46	1240.9
MDI 15%	50/50	4	3	0.880	2.33	674.4
MDI 20%	50/50	4	3	0.932	4.05	1144.8
MDI 30%	50/50	4	3	0.994	4.27	770.8
MDI 15%	25/75	4	3	0.855	3.12	808.0
MDI 20%	25/75	4	3	0.861	3.64	889.5
MDI 30%	25/75	4	3	0.924	4.22	942.4
MDI 20%	0/100	4	3	0.742	3.09	739.3
MDI 30%	0/100	4	3	0.834	5.93	1053.3
MDI 40%	0/100	4	3	0.861	7.69	989.5

Table 5. Mechanical properties of particle boards for structural application [26].

Thickness (mm)	>6-13	>13-20	>20-25	>25-32	>32-40	>40
$\boldsymbol{f_{c,p,k}}$ $(\boldsymbol{MPa})$	12.0	11.1	9.6	9.0	7.6	6.1
$\boldsymbol{E_{c,p}}$ $(\boldsymbol{MPa})$	1800	1700	1600	1400	1200	1100
$\boldsymbol{\rho_{p,k}}$ $(\boldsymbol{g/cm^3})$	0.650	0.600	0.550	0.550	0.500	0.500

$\boldsymbol{f_{c,p,k}}$: Compressive strength characteristic value; $\boldsymbol{E_{c,p}}$: Average elastic modulus in compression; $\boldsymbol{\rho_{p,k}}$: density characteristic value.

Figure captions

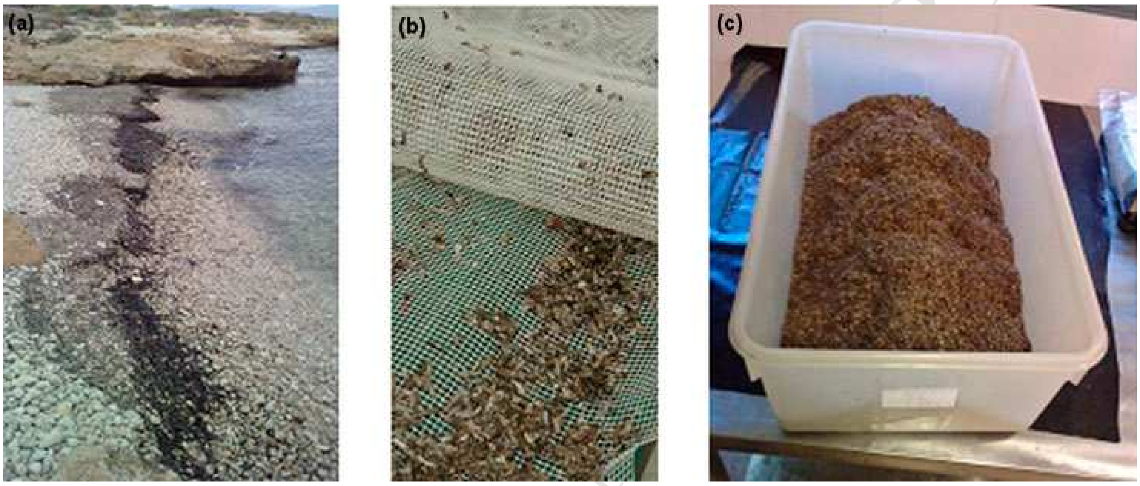

Fig. 1. (a) Posidonia oceanica before recollection. (b) Cleaning process by submerging in water. (c) PO particles after crushing and sieving.

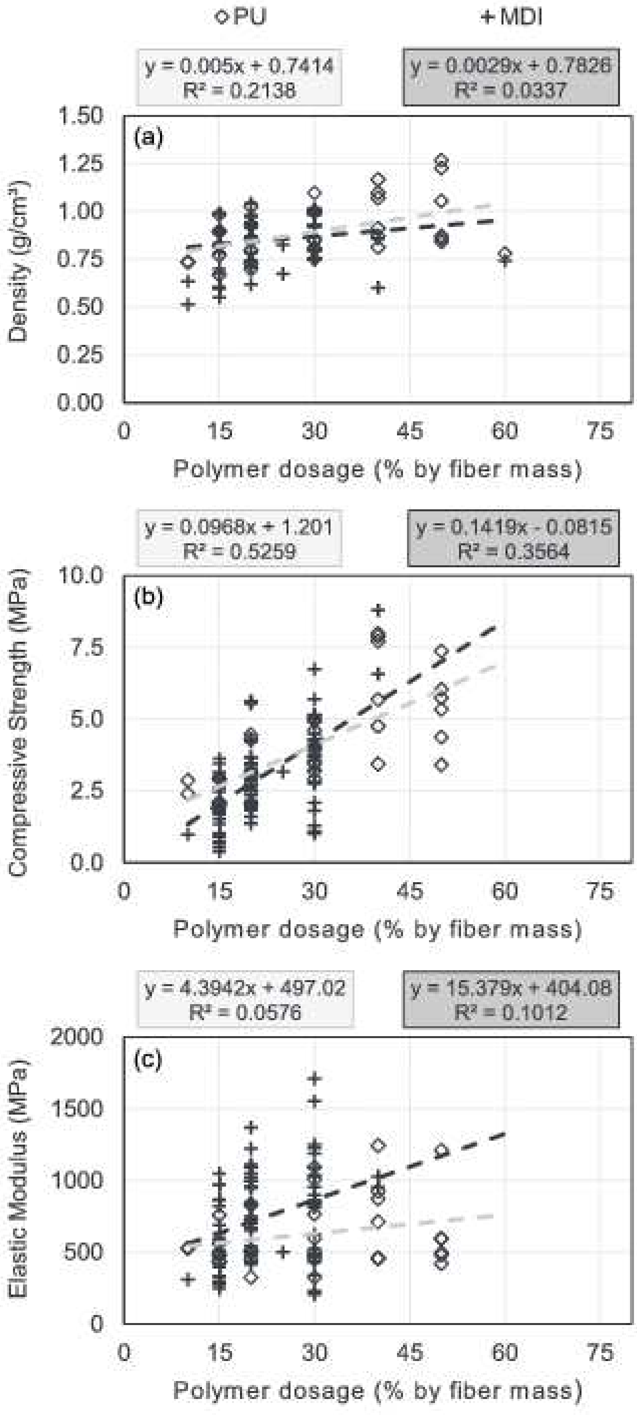

Fig. 2: Mechanical properties of Posidonia-Wood biocomposites in PU or MDI matrix: (a) Density, (b) compressive strength, and (c) elastic modulus.

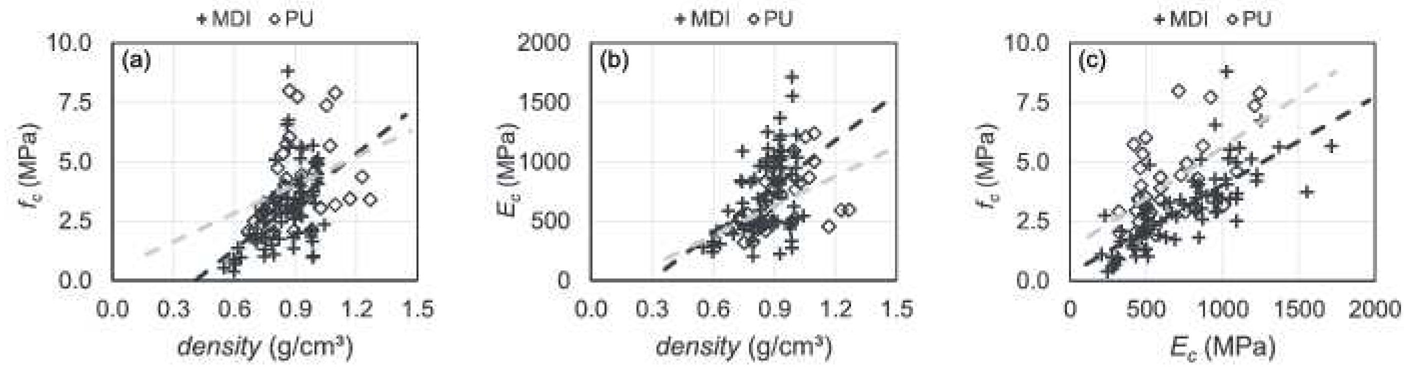

Fig. 3: Mechanical properties relationships of Posidonia-Wood biocomposites in PU or MDI matrix: (a) compressive strength vs density, (b) elastic modulus vs density, and (c) compressive strength vs elastic modulus.

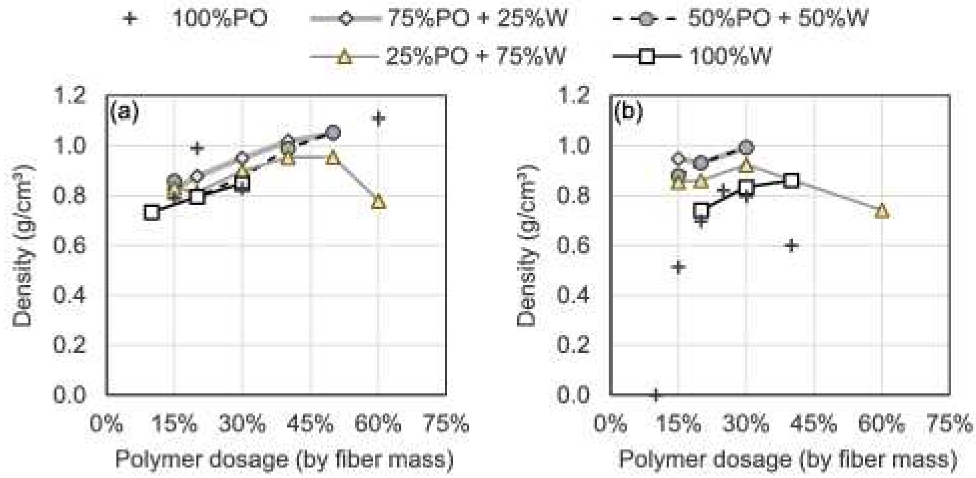

Fig. 4: Density for composites with different PO/W ratios: (a) PU matrix, (b) MDI matrix.

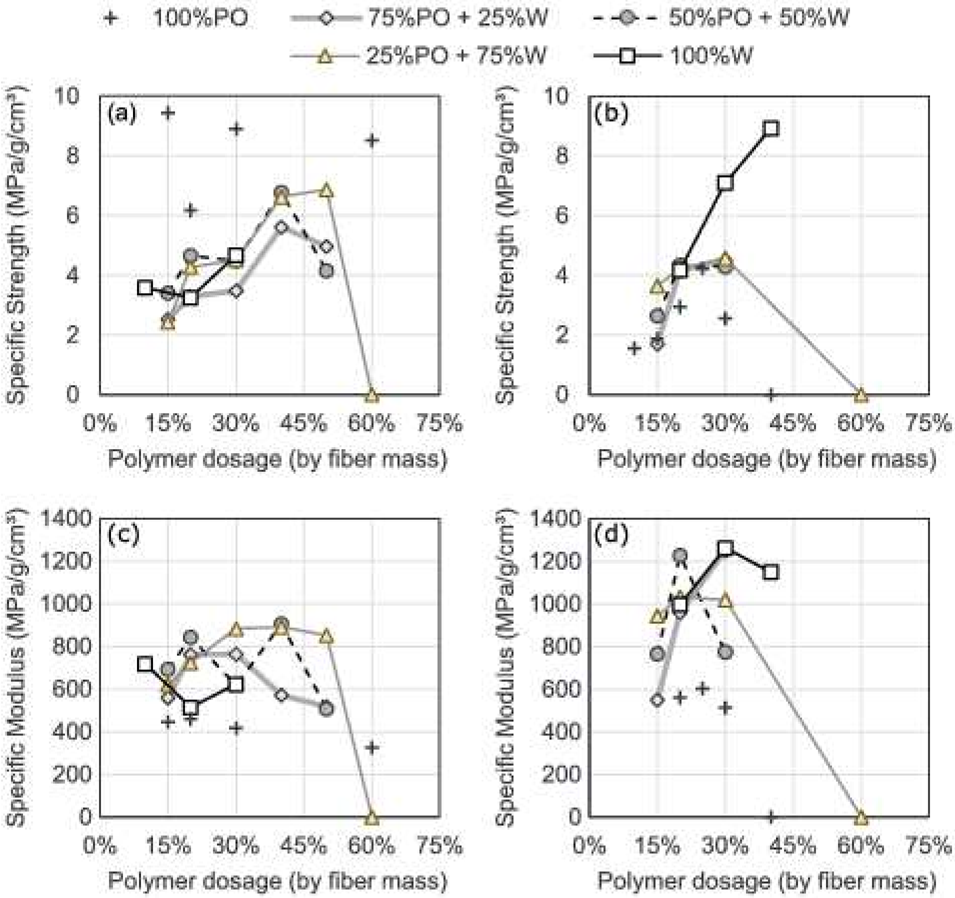

Fig. 5. Specific compressive strength and elastic modulus for composites with different PO/W ratios: (a) and (c) PU matrix, (b) and (d) MDI matrix.

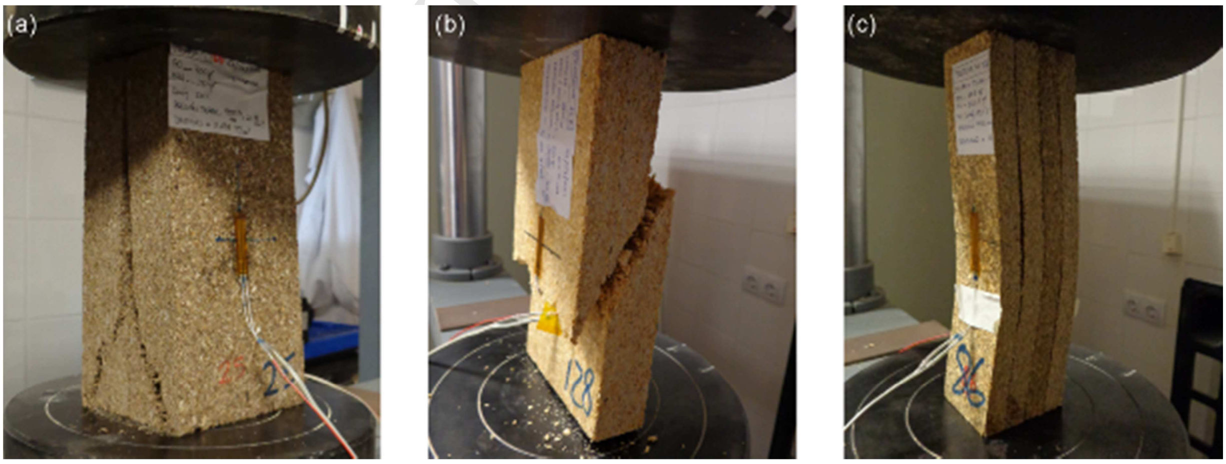

Fig. 6: Failure modes: (a) support failure (b) board maximum strength, and (c) buckling.

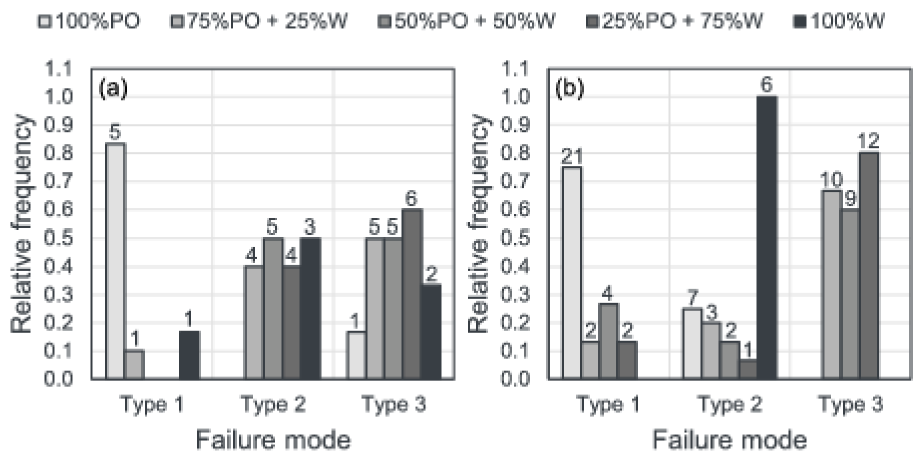

Fig. 7: Prevalence of each failure mode for different PO/W ratio (absolute frequencies are shown in each bar and relative frequencies in vertical axis) in (a) PU matrix or (b) MDI matrix.