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Flexural behavior and water absorption of asymmetrical sandwich composites from natural fibers and cork agglomerate core

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ABSTRACT

This work addresses an experimental investigation concerning flexural and water absorption behavior of a novel low-cost green composite asymmetric sandwich. For specimen manufacturing, an agglomerate cork panel and natural fiber reinforcements, namely basalt and flax fiber were used. A bio-based epoxy resin was used as matrix and the specimens were manufactured using vacuum assisted hand lay-up. For some specimens the core material was altered allowing resin infiltration between the granules. Results show that both, the core type and specimens' stance influence the flexural behavior. More importantly, all specimens showed a very good energy absorption behavior during bending tests. The water absorption of the specimens was significantly reduced by the infiltration of resin inside the core material. These attractive performances reveal that the green composites based sandwich proposed in this work can be a good alternative to traditional ones.

1. Introduction

Environmental concerns and increasingly social pressure for the use of less harmful composites materials have aroused a paradigm shift towards using natural fibers as substitute for synthetic and nonrenewable reinforcements. This fact has given rise to what is commonly called "Green Composites", namely those obtained from lower environmental impact raw materials from biodegradable or renewable sources. Such ecofriendly raw materials can be naturals fibers extracted from plants as flax or hemp [1,2], or those having a mineral origin as basalt fiber. Natural fiber like hemp, sisal, basalt, has been extensively studied during the last years [3]. Recent developments in the field of composites materials have shown that "*Green Composites*" can be, from the viewpoints of mechanical performance, manufacturing costs and environmental footprint, a good alternative to traditional reinforcements [4–6]. Masoodi et al. [7] combined cellulose fibers with bio-based epoxy mainly obtained from co-products of bio-fuel production, and results showed significant mechanical properties. However, significant obstacles for structural applications of "Green composites" still exist. These obstacles include low thermal stability during processing, hydrophilic nature, poor adhesion with matrix and trustfulness in the use of natural fibers and their composites. Also, sandwich structures are increasingly used in transportation vehicles and civil infrastructures due to their high stiffness/strength-to-weight ratio. Nevertheless in most of these applications, sandwiches are mainly manufactured in the conventional symmetric configuration [8–10], besides only a few studies deal with the asymmetrical configuration [11–13]. The objectives of the present work are to manufacture basalt/flax/cork asymmetric sandwich via a low cost manufacturing process and to investigate the effects of the loading conditions during three-point bending tests and the water absorption behavior.

2. Materials and methods

For the present work, flax-cork-basalt (FCB) bio-based epoxy sandwiches have been manufactured using vacuum assisted hand lay-up process (Fig. 1). Basalt fiber fabric (400 g/m^2, Kammeny Vek, Russia) was used as reinforcement for one of the two face-sheets of the asymmetric sandwich panels. The other face-sheet was made of flax fabric (200 g/m^2, Lineo, Belgium). Bio-based epoxy resin system (SuperSap 100/1000, Entropy Resins) was used as matrix. SuperSap 100/1000 is a bio-based epoxy system with a bio-content per mass up to 37%, where petroleum-based raw materials have been substituted with bio-based ones. Commercially available cork board (CORECORK ®NL20, Amorim Corporation, Portugal) was selected as core material [14]. After the hand

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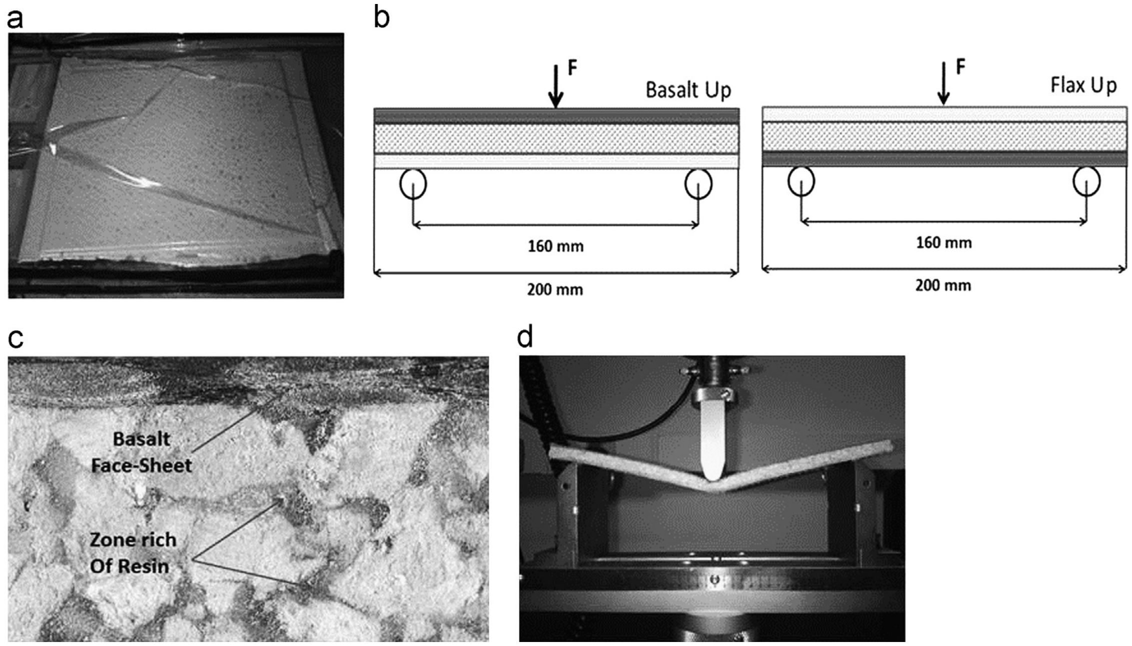

Fig. 1. (a) Bagging process, (b) test configurations, (c) resin infiltration inside core and (d) specimen during bending test.

Table 1
References and characteristics of the specimens.

Specimen	Manufacturing process [a]	Length (mm)	Wide (mm)	Mean thickness (mm)	Number of face-sheet layers[b]	Test[c] type and position of the sample[d]	Number of specimens
3 layers-modified core (**3L-MC**)	VA	200	30	8.52	3F/3B	TBT, FU,BU	10
2 layers-modified core (**2L-MC**)	VA	200	30	7.55	2F/2B	TBT, FU,BU	10
3 layers-original coated cor (**3L-OC**)	VAC	200	30	8.48	3F/3B	TBT, FU,BU	10
2 layers-original coated core (**2L-OC**)	VAC	200	30	7.54	2F/2B	TBT, FU,BU	10
Modified core (**MC**)	VA	25	25	5	–	FCT	5
Original coated core (**OC**)	Manual coating	25	25	5	–	FCT	5

[a] VA: vacuum assisted hand lay-up; VAC: vacuum assisted hand lay-up, with previous core coating.
[b] 2F/3F: 2/3 layers of flax, 2B/3B: 2/3 layers of basalt.
[c] TBT: three-point bending test; FCT: flatwise compression tests.
[d] Basalt Up (BU) or Flax Up (FU).

laying-up step, vacuum bagging operation was performed to ensure a good adhesion between each components of the sandwiches. This operation is a very important step in obtaining a good quality part. All the sandwich panels were removed from the vacuum bag after 24 h, and then post cured for 2 h at 50 °C in an oven. A second batch of specimens was obtained by the same manufacturing process, but the main difference resides in the fact that the cork sheets was previously coated with a very thin layer of resin and cured for 24 h at room temperature to prevent resin infiltration inside the core during vacuum bagging operation. The resulting $500 \times 900\ \text{mm}^2$ panels were cut into specimens of 200 mm length, 30 mm wide using diamond-tipped circular saw, see Table 1.

Flexural strength was determined for all the specimens, using three-point bending test method in accordance with ISO 14125. Tests were performed using Instron 5960 universal testing machine equipped with a 30 kN load cell at a rate of 2 mm/min (Fig. 1d). Since sandwich specimens were asymmetric, each type of specimen has been tested in two different stances (Basalt Up or Flax Up) as shown in Fig. 1b.

Flatwise compression tests on the two different core materials were performed following EN ISO 844 standard. Squared specimens of 25 mm sides were tested under controlled displacement at a rate of 0.5 mm/min. For each core type, ten identical specimens were tested and average result was obtained.

To determine the water absorption behavior, tests were conducted in accordance to ASTM D 570. Five specimens from the different sandwich panels were immersed in de-ionized water bath, at room temperature (23 °C) and atmospheric pressure. The amount of water absorbed was measured every 24 h for 12 days. After each time period, the specimens were taken out from the water and first dried using tissue paper to remove the excess of water on the surface before the weight was recorded (W_b). The same procedure was applied to specimens of infused (MC, *modified core*) and non-infused cork panels (OC, *original coated core*). The percentage of apparent weight gain was then calculated according to

$$\text{Water absorption } (\%) = \frac{W_a - W_b}{W_b} \qquad (1)$$

3. Results and discussion

Effect of the manufacturing process on the core material: It was observed that for the core material without resin coating (OC), the

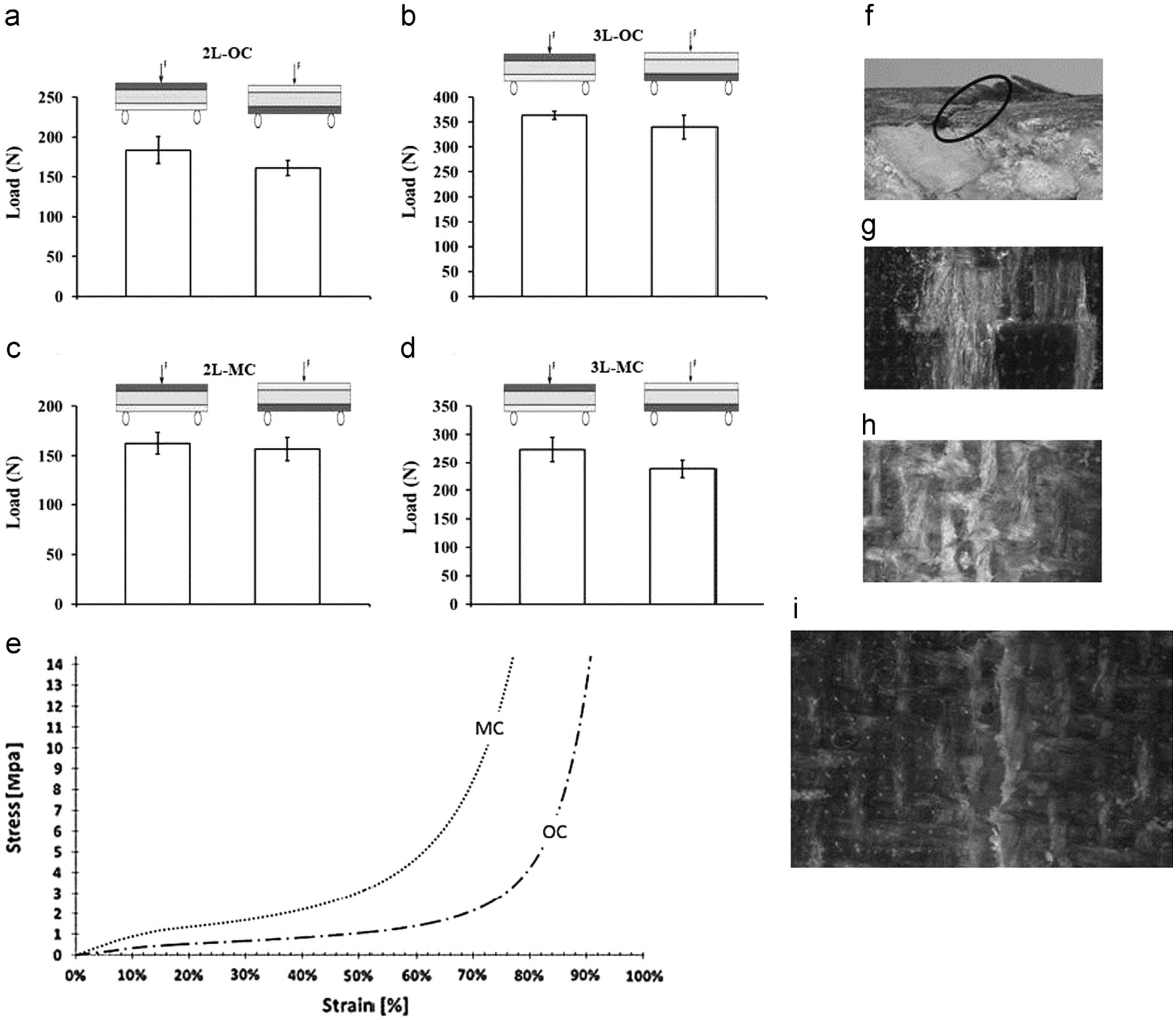

Fig. 2. (a–d) Mean maximum load values obtained from three-point bending tests; (e) stress vs strain curves of core during compression test, (f and g) basalt fiber compressive failure, (h) flax fiber failure compressive failure and (i) flax fiber tensile failure.

resin infiltrate through the space between the cork granules during the manufacturing process, therefore the density is affected. With the aim to evaluate the density increase, this property was determined from the geometric parameters and weight. In order to minimize the error in determining the specimen density, the dimensional parameters of the specimens were measured at five different positions. For each specimen the density resulted by dividing the weight to its volume. The calculated density for a resin infiltrated cork was found to be of about 325 kg/m^3, thus an increase of 38% compared to the original cork panel.

Mechanical behavior: Average peak values obtained during the three-point bending tests are shown in Fig. 2(a–d). As can be observed in Fig. 2(a and b), specimen stance does not influence significantly these load values for the 2L-OC and 2L-MC specimens. However, specimens tested in basalt-up stance achieve a slightly higher peak load compared to flax-up stance. Comparing the 3L-OC/3L-MC and 2L-OC/2L-MC is possible to observe, that as the number of fabric layers increases from 2 to 3, the peak values increase significantly for both test configurations, as expected. Focusing on core materials, 2L-MC/3L-MC shows considerably better performance than 2L-OC/3L-OC, accordingly resin infiltration inside cork (Fig. 1c) core might have a positive influence on the enhancement of the overall flexural strength of the specimens.

Subsequently, in order to understand the influence of asymmetric sandwich construction on the bending behavior, closer examination of load–displacement curves was performed. Fig. 3(a and b) shows representative load–displacement curves where different key features can be observed: initial linear elastic region at very low deflection followed by a more significant elasto-plastic region until a peak value is reached after which the load decreases [15]. Regardless of the load drop mechanism all the curves tend towards a plateau.

It is interesting to note that the kind of rupture mechanism is strongly influenced by the test configuration as well as the core type (Fig. 2). For specimens with modified core, when basalt layers act as upper face-sheet, the sandwiches undergo a sequence of three failure mechanism: initial failure begins at lower face-sheet, and subsequently crack grows through the core and finally delamination between core and upper face-sheet occurs. Abrupt load drop caused by the rupture of bottom face-sheet (Fig. 2i) shows the poor load bearing capacity of flax under tensile load. This behavior may also be unfortunately connected to the fact that

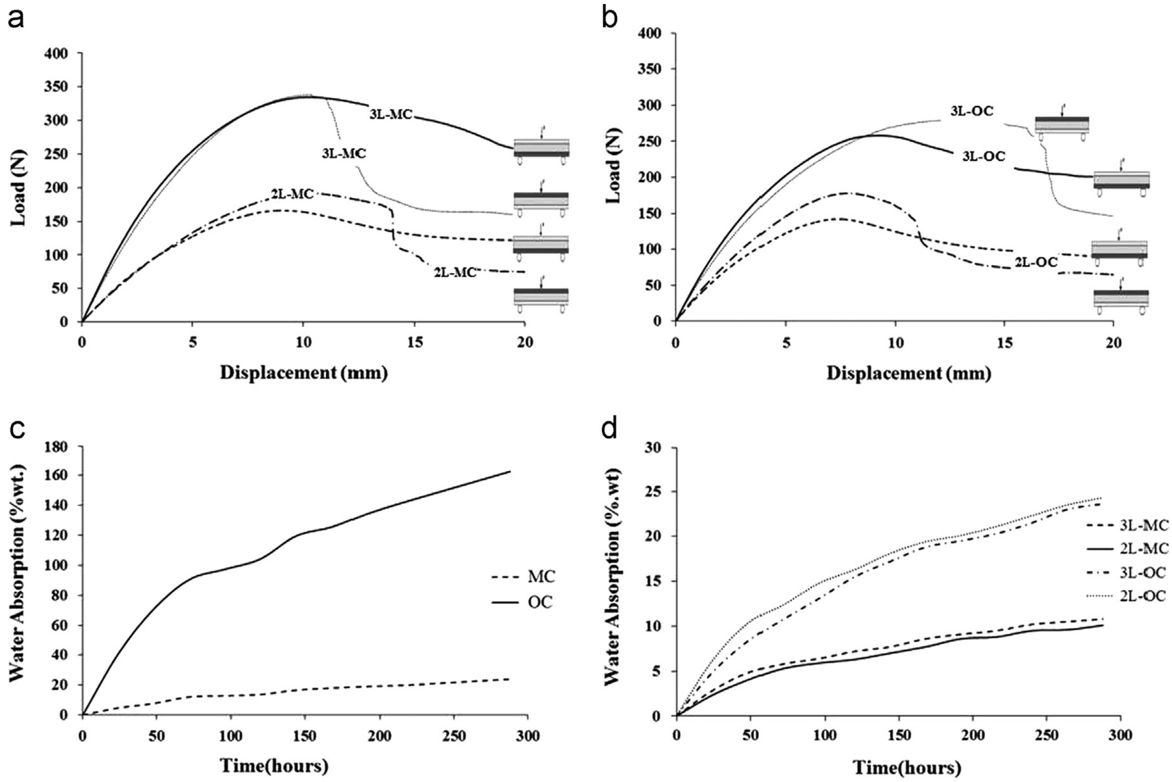

Fig. 3. (a) Load–displacement curves of sandwich specimens with modified core, (b) load–displacement curves of sandwich specimens with original core, (c) water absorption curves for different sandwich specimens and (d) water absorption curves for different core specimens.

modified core as shown in Fig. 1c, being more rigid is more prone to crack growth.

For specimens with unmodified core, as the core is not rigid enough to support the stress, the upper face-sheet shows catastrophic shear failure (Fig. 2g) and no significant damage appear at the bottom face-sheet.

At difference, when flax fiber layers act as upper face-sheet (Fig. 3a and b), specimens show the following failure sequence: initial compressive failure followed by core densification [16]. After reaching peak load, only slight load loss can be observed and the specimens then continued to carry significant load [15]. No significant failure was observed in the lower basalt face-sheet. The average load in the plateau region remains quite significant. Observation of the sandwich after failure shows matrix cracking and face-sheet wrinkling (Fig. 2h) at the load application point. The high energy absorbing capability of asymmetric sandwich specimens in this test configuration is attributed to the fact that basalt bottom face-sheet can provide significant flexural strength for the whole specimens after failure of flax top face-sheet.

It can be clearly seen in Fig. 2e that the modified cork panel becomes stiffer and offers better resistance to deformation under compressive load. The resin surrounding the cork granules deflect the stresses along the interfaces delaying the compressive deformation during loading under flexural tests [17].

The maximum and minimum coefficient of variation values registered for all the tests were 2.29% (3L-MC, Flax Up) and 9.23% (2L-MC, Basalt Up). The low variation of the flexural properties supports the potential of the asymmetric sandwich proposed.

Water absorption: Fig. 3(c and d) shows the percentage of weight gain as function of time for sandwich specimens and cork panels (OC, MC). As expected, cork specimens with unmodified core show a water uptake value reaching about 160 wt%. Thus water uptake of those specimens is largely due to the presence of free space between the cork granules. In the case of the infused core specimens the water uptake is around 20 wt%; evidencing that the infiltration of the resin in the core significantly reduces the amount of water absorbed. In the case of sandwich composites, the maximum percentage weight gain was observed for the specimens with coated core; the mean value is about 24 wt%. In contrast, sandwich specimens with modified core show only 10 wt%. This remarkable decrease in water uptake percentage is likely a result of the presence of resin inside the core, thus reducing the exposed cork surface [18]. It is worth noting that the addition of reinforcing layers only caused a slight change in the water absorption capacity of the sandwich specimens.

4. Conclusion

A novel asymmetric green composites sandwich was successfully manufactured by a low cost method and tested under three-point bending. The presence of different fiber face-sheets heavily influences the failure mechanism and also shows significant enhancement of the energy-absorbing capability when specimens are loaded in the proper conditions. Furthermore, resin infiltration inside the core may be beneficial in some cases, thus reducing water absorption. The results suggest that use of natural fibers as reinforcement for bio-based matrix may be a potential candidate to manufacturing daily industrial applications such as interiors aesthetic panels or doors in mass transport vehicles while preserving environmental friendliness and cost effectiveness.

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