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Cork Agglomerates as an Ideal Core Material in Lightweight Structures

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Abstract

The experiments carried out in this investigation were oriented in order to optimize the properties of cork-based agglomerates as an ideal core material for sandwich components of lightweight structures, such as those used in aerospace applications. Static bending tests were performed in order to characterize the mechanical strength of different types of cork agglomerates which were obtained considering distinct production variables. The ability to withstand dynamic loads was also evaluated from a set of impact tests using carbon-cork sandwich specimens. The results got from experimental tests revealed that cork agglomerates performance essentially depends on the cork granule size, its density and the bonding procedure used for the cohesion of granulates, and these parameters can be adjusted in function of the final application intended for the sandwich component. These results also allow inferring that optimized cork agglomerates have some specific properties that confirm their superior ability as a core material of sandwich components when compared with other conventional materials.

Keywords: sandwich structures, cork agglomerates, impact, flexural strength.

1. Introduction

The use of lightweight structures with high strength to weight ratio has been an enduring characteristic in the transport industry. The rising demand for new materials has induced a significant growth in sandwich composite technology, where sandwich core laminates are used to stiffen various composite applications such as boat hulls, automobile hoods, train structures and aircraft panels. The commonly used core materials are honeycombs, foams and balsa wood, but recent developments resulted into new alternatives, such as cellular core structures [1].

The properties of primary interest for the core materials can be summarised as: low density, high shear modulus, high shear strength, elevated stiffness perpendicular to the faces and both good thermal and acoustic insulation characteristics [1, 2]. Some properties of cork agglomerates suggest that this natural material can evince some remarkable properties when performing as a core of a sandwich component, namely a high damage tolerance to impact loads, good thermal and acoustic insulation capacities and excellent damping characteristics for the suppression of vibrations [3, 4].

Cork has an alveolar cellular structure similar to that of a honeycomb, and its cells are mostly formed by suberin, lignin and cellulose. This cellular configuration has a strong influence on the mechanical properties of cork based materials [5]. Silva et al. [6] present a compilation of the main mechanical properties of natural cork obtained from different experimental tests. At a first glance, one could conclude that natural cork has a poor mechanical behaviour when compared with other types of core materials, such as synthetic foams. However, for some specific applications, cork can compete with these materials. In fact, when comparing the specific compressive strength (σ_c/ρ) against the specific modulus (E/ρ), cork has a better mechanical behaviour than flexible polymer foams and comparable to some rigid polymer foams. Also, its low thermal conductivity combined with a reasonable compressive strength make it an excellent material for thermal insulation purposes as well as for applications in which compressive loads are present.

The proper design and application of sandwich construction depends on a throughout characterization and understanding of the sandwich constituent materials (face sheets, core, and adhesive), and also of the whole structure under quasi-static and dynamic loading scenarios. In this latter case, sandwich structures are often susceptible to foreign object damages resulting from impacts [7]. Therefore, the performance of structural sandwich parts under impact loading has to be considered in many cases. Aircraft, rail and road vehicles can be exposed to local impact with small, but possibly heavy objects, such as runway/roadway debris, tool drops, hail, bird strikes, stones or ice, and also during the loading and unloading of cargo. Boats and ships can encounter loads on the hull in collision with floating objects when cruising or during manoeuvres in the harbour. Horizontal surfaces, such as ship decks or aircraft floors can be subjected to impacts from almost any dropped object. Which object creates the most significant damage is a matter of circumstance. A small object dropped from a great height may create more damage than a large object dropped from only a few centimeters [8-11]. Sandwich beams are also being increasingly used in applications requiring high bending stiffness and strength combined with low weight [12].

The study herein presented lays stress upon in three-point bending tests of simply supported sandwich panels, consisting of carbon/epoxy face sheets and three different types of core materials: Nomex®, Rohacell® 71 WF rigid foam and cork agglomerates. At a first stage, three types of commercial cork agglomerates (with different granule sizes) were tested evincing a poor mechanical performance when compared to conventional core materials. In order to improve the mechanical behaviour of cork as a core material, three new types of cork agglomerates were fabricated with conventional cork granulates but using epoxy resin as adhesive element. A set of impact tests of different types of sandwich specimens were carried out, as well as thermal conductivity analysis, aiming the characterization of the new cork agglomerates on a comparative basis with other core materials having top mechanical performances.

2. Experimental Procedures

2.1 Constituent materials and fabrication process

The face sheets of the sandwich panels were made of three 0º/45º/0º plies of carbon/epoxy prepreg (STA199-45-005 for the bending tests specimens and PN900-C08-45&D2358 for the impact test specimens), resulting in a final laminate with an average thickness of 1.3 mm and a fiber volume content of 54% (STA199-45-005) and 50% (PN900-C08-45&D2358), after autoclave curing. Table 1 lists the main mechanical properties of these carbon-epoxy composites.

Table 1. Main properties of carbon-epoxy laminates used in the face sheets

Composite reference	Density [kg/m^3]	FVC standard [%]	Tensile strength [MPa]
STA 199-45-005	1760±40	50	550
PN900-C08-45	1530±30	54	540

FVC = Fiber Volume Content

Tables 2 and 3 present the density and main geometric parameters of eight types of core materials considered for comparative purposes, namely: Nomex® and Rohacell® (which are conventional core materials, each with high specific strengths within its class), commercial cork agglomerates (referenced as 8123, 8810, 8303, 8822 and NL30 from Amorim Cork Composites) and cork agglomerates developed in this work using epoxy resin (referenced as 2/3, 3/4 and Mixed, see section 2.1.1). Table 3 also indicates the final sandwich panel dimensions for each of the previously mentioned materials. These dimensions (referred to Figure 1) are not the same for all the specimens due to some discrepancies between commercial available materials and those agglomerates specifically developed in this investigation that, in turn, had to be constrained by the mould dimensions regarding the requirements of the flexural tests imposed by ASTM C393-00 [13]. Considering the simply supported sandwich beam loaded in a three-point bending configuration as sketched in Figure 1, L is the beam length between the supports, c the core thickness, t the face thickness and d the panel thickness (b, not represented in this figure, is the width of the beam). The transverse mid point deflection is due to an applied transverse load P.

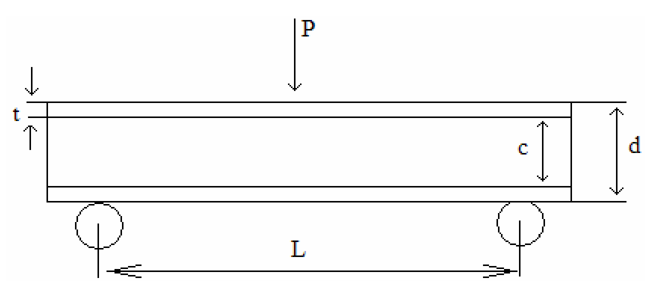


Figure 1 – Geometry of sandwich beam

Table 2. Density of core materials used in three-point bending and impact tests

Core material reference	**Density [kg/m^3]**
Rohacell® 71 WF	75
Nomex®	48
8123	270
8810	137
8303	224
8822	155
2/3	272
3/4	274
Mixed	162
NL30	266

Table 3. Main geometric parameters of sandwich specimens used in three-point bending tests

<table>
<tr><th>Core material reference</th><th>b [mm]</th><th>c [mm]</th><th>d [mm]</th><th>L [mm]</th></tr>
<tr><td>Rohacell® 71 WF</td><td rowspan="5">50</td><td>15</td><td>17.6</td><td rowspan="5">270</td></tr>
<tr><td>Nomex®</td><td rowspan="4">12</td><td rowspan="4">14,6</td></tr>
<tr><td>8123</td></tr>
<tr><td>8810</td></tr>
<tr><td>8303</td></tr>
<tr><td>2/3</td><td rowspan="3">45</td><td>15</td><td>17,6</td><td rowspan="3">150</td></tr>
<tr><td>3/4</td><td>12,8</td><td>15.4</td></tr>
<tr><td>Mixed</td><td>14.2</td><td>16.8</td></tr>
</table>

Six types of core materials with different densities were considered for the fabrication of the specimens used in the impact tests, namely: optimized cork-epoxy agglomerates (2/3, 3/4 and Mixed), conventional cork agglomerates (NL30, 8822) and Rohacell® 71 WF. The final sandwich panels were 150 mm square having a nominal thickness of 30 mm. These panels were fabricated by bonding the carbon-epoxy face sheets to the core material with a thermosetting modified epoxy structural adhesive in a film form (reference FM300-080PSF&09BV7). The face sheets and core were bonded together and cured in an autoclave following the fabrication cycle provided by the prepreg manufacturer.

2.1.1 Development of cork agglomerates with enhanced mechanical properties

As previously mentioned, one major goal of this investigation was to develop a new cork based composite with improved mechanical properties when compared to similar cork products which are currently commercially available. Consequently, three new types of cork agglomerates consisting of cork granules and epoxy resin were fabricated in order to obtain a better overall specific strength. These agglomerates were based on different granule sizes being referenced as 2/3 (small granule size), 3/4 (large granule size) and Mixed (mixture of small and large granules, equal proportion). The challenge in the preparation process of the agglomerates was related with the effective agglomeration method and the right cork/resin ratio. After some experiences the right resin proportion was found to be within the range 24% to 30%, depending on the used granulate. The preparation process (as schematized in Figure 2) begins with the mixture of cork granules and epoxy resin in the proportions indicated in Table 4. This mixture is then put in a mould and covered with a steel plate being compressed in a hydraulic press (the pressure level varies as shown in the table). The last step consists of placing the mould in a heater at a constant temperature of 80ºC during two hours, as to guarantee a convenient curing stage.

Figure 2 – Scheme of the fabrication process used for obtaining the cork-epoxy agglomerates

Table 4. Optimized cork agglomerates preparation parameters

Cork agglomerate type	Cork granule mass [g]	Resin percentage by weight	Agglomeration pressure [bar]	Cure process
2/3	270	24%	50	2 Hours (at 80ºC)
3/4	270	24%	60	2 Hours (at 80ºC)
Mixed	150	30%	15	2 Hours (at 80ºC)

2.2 Three-point bending tests

Three-point bending tests were performed using two universal testing machines: a digitally controlled servo-hydraulic Instron 8502 (with a 20 kN load cell and an actuator velocity of 12 mm/min) and an electromechanical Zwick 1435 (with a 5 kN load cell and an actuator velocity of 5 mm/min). According to ASTM C393-00 [13], the test specimens had a rectangular cross section with the geometric parameters indicated in Table 3, being simply supported on cylindrical rollers. The core shear stress, facing bending stress and the panel shear rigidity are determined as recommended by ASTM C393-00 standard, using the following expressions:

$$\tau = \frac{P}{(d+c)b} \tag{1}$$

$$\sigma = \frac{PL}{2t(d+c)b} \tag{2}$$

$$\Delta = \frac{PL^3}{48D} + \frac{PL}{4U} \quad \text{or} \quad U = \frac{PL}{4\left(\Delta - \frac{PL^3}{48D}\right)} \tag{3}$$

$$D = \frac{E\left(d^3 - c^3\right)b}{12} \tag{4}$$

Where:

τ - core shear stress, [MPa]

P - load, [N]

d - sandwich thickness, [mm]

c - core thickness, [mm]

b - sandwich width, [mm]

σ - facing bending stress, [MPa]

L - span length, [mm]

t - facing thickness, [mm]

Δ - total beam midspan deflection, [mm]

D - panel bending stiffness, [Nmm^2]

E - facing modulus, [MPa]

U - panel shear rigidity, [N]

2.3 Impact tests

An IMATEK drop tower apparatus with a free-falling mass was used to impact the sandwich plates (Figure 3). The hemispherical impactor surface had a radius of 20 mm and the dropped carriage had a total mass of 3 kg. The sandwich panels were constrained in each lateral side as shown in Figure 3b. All the specimens were subjected to the same energy level (about 23 J), with an impact velocity of 4 m/s resulting from a drop height of 0.8 m. Impact loads were acquired with a piezoelectric force transducer located between the impactor and the carriage.


(a)

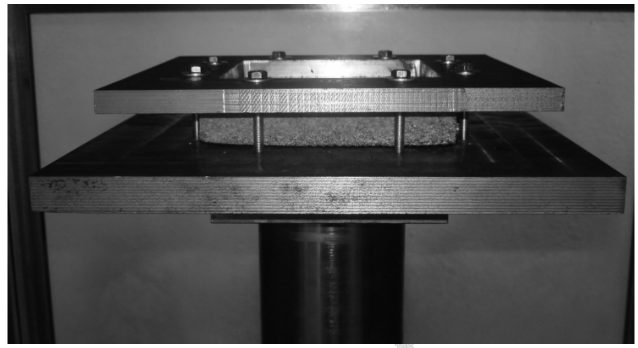

(b)

Figure 3 – Impact testing equipment: (a) drop tower; (b) clamped sandwich specimen

As a consequence of the absence of a specific standard impact test method for sandwich structures, impact tests were performed observing the recommendations of ASTM D7136/D7136M-05 [14], which suggests the following expressions for obtaining the main testing results:

$$E_i = \frac{m\, v_i^2}{2} \tag{5}$$

$$\delta(t) = \delta_i + v_i + \frac{g\, t^2}{2} - \int_0^t \left(\int_0^t \frac{F(t)}{m}\, dt \right) dt \tag{6}$$

$$E_a(t) = \frac{m\left(v_i^2 - v(t)^2\right)}{2} + m\, g\, \delta(t) \tag{7}$$

Where:

E_i - impact energy, [J]

m - impactor mass, [kg]

v_i - impact velocity, [m/s]

g - acceleration due to gravity (9,81 m/s^2)

v - impactor velocity at time t, [m/s]

F - impactor contact force at time t, [N]

δ_i - impactor displacement from reference location at time t = 0, [m]

δ - impactor displacement at time t, [m]

E_a - absorbed energy at time t, [J]

2.3 Thermal conductivity tests

As a final characterization parameter of the optimized cork based materials, thermal conductivity tests were performed only in two types of cork-epoxy agglomerates with improved mechanical characteristics, namely 2/3 and Mixed. The specimens had a 200x200 mm square shape with a nominal thickness of 30 mm, according to standards ISO 2582 [15] and EN 12664 [16], both concerning the hot plate method. This method, illustrated in Figure 4, consists of establishing a fixed thermal gradient across the sample, which is accomplished by placing the sample between two surfaces with accurately controlled temperatures. The environment of the sample compartment is controlled for precise *K-factor* determination due to a fixed temperature differential resulting from a cold plate set at 10ºC and a hot plate set at 37ºC. These temperatures are closely controlled with proper sensors, high gain controllers and heat sinks. The heat flow through the sample is measured with a heat flow transducer

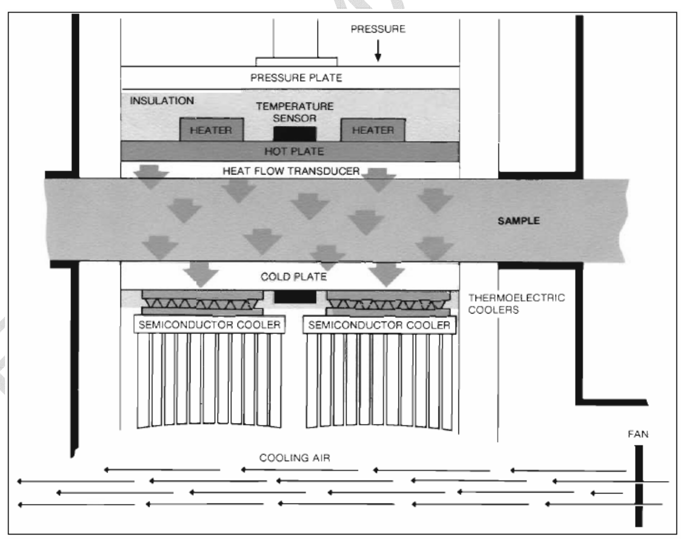


Figure 4 – Operation scheme of the hot plates method

3. Results and discussion

3.1 Three-point bending tests

Figure 5 presents a set of force-displacement curves which are related with sandwich specimens with similar dimensions but using different types of core materials, namely: honeycomb

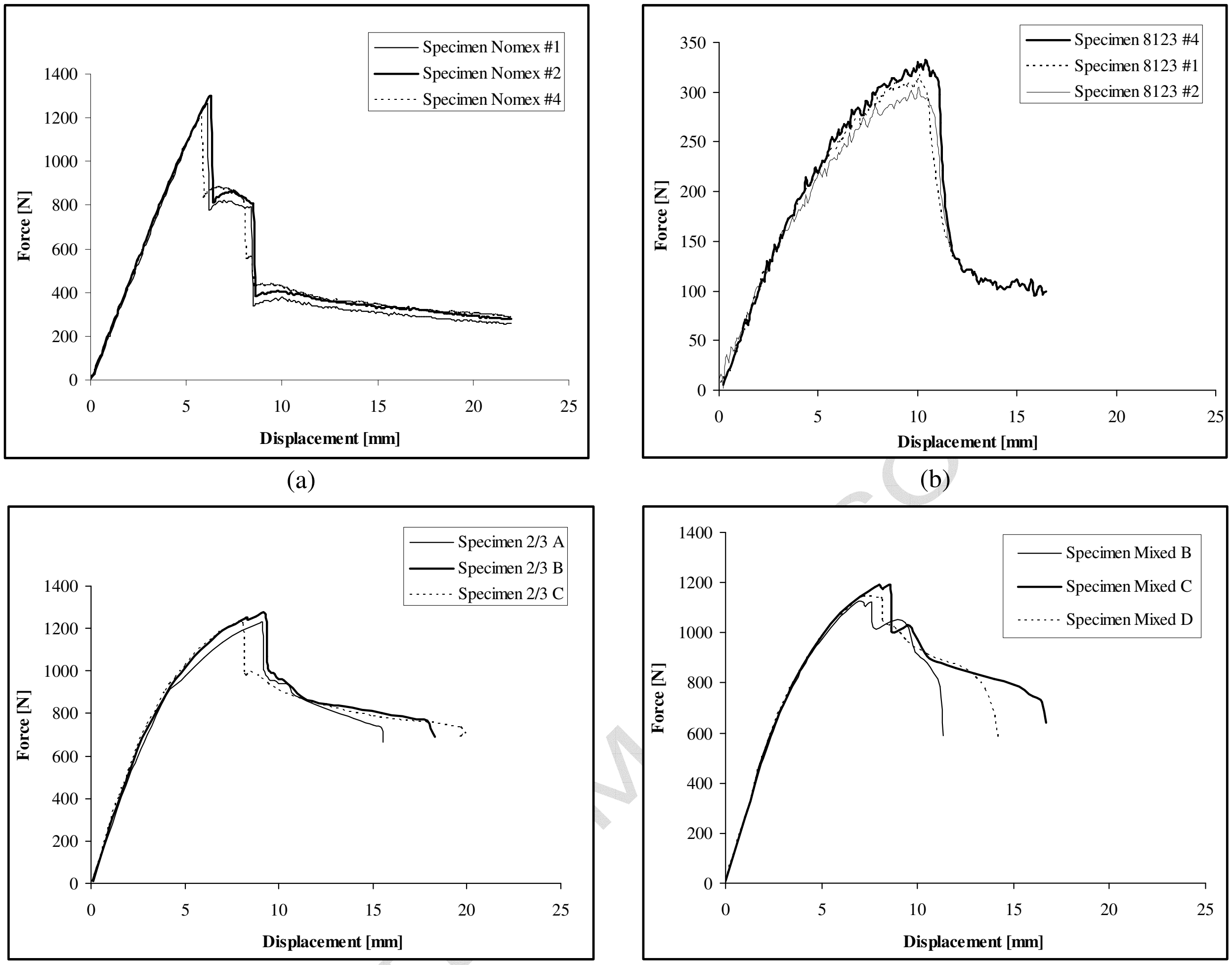
(Nomex®), commercial cork agglomerates (ref. 8123, small granule size) and cork-epoxy agglomerates with distinct granule size (2/3 and Mixed). Due to the significant amount of core materials considered for testing purposes, only four cases are graphically represented. However, flexural strength of specimens using other types of core materials was also evaluated, including Rohacell® foam and commercial cork agglomerates with different granule sizes: 8303 (medium granule size) and 8810 (largest granule size).

Table 5 shows the maximum core shear stress and face bending stress values as obtained from equations (1) and (2), respectively. The highest maximum core shear stress is verified for the Nomex® core sandwiches, followed by the cork-epoxy agglomerate cores (between 1% to 12% lower than Nomex®, 38% to 56 % higher than Rohacell® rigid foam and 4 to 7 times higher than the commercial cork agglomerates). In spite of the maximum face bending stress and panel shear rigidity values that have been observed in the Nomex®/carbon and Rohacell®/carbon sandwiches (Table 6), the cork-epoxy sandwich panels clearly present higher values concerning these stresses when compared with the commercially available conventional cork agglomerates (three times higher).

Also, it is interesting to notice that apparently there is not any clear effect of the cork granule size on the core shear stress and face bending stress obtained for the different types of cork agglomerates, since for the case of commercial agglomerates the maximum values were verified for the smallest granule size core (8123), whilst a higher strength was obtained for the highest granule size in the case of the produced cork-epoxy agglomerates.

All the curves of Figure 5 present an elastic linear behaviour since the beginning of the loading stage, but there is a slight plastic deformation for higher displacements in the case of cork agglomerates. This fact is related with the different fail mechanisms verified in each of the core materials. In fact, Nomex®/carbon sandwich evinces a localized failure in the high stress concentration region of contact between the loading actuator and the material (as visible in Figure 6a), but the damage affecting the cork /carbon sandwiches begins with a small shear crack which propagates from the loaded zone following the direction of the middle plane towards the tips of the specimen (Figure 6b).

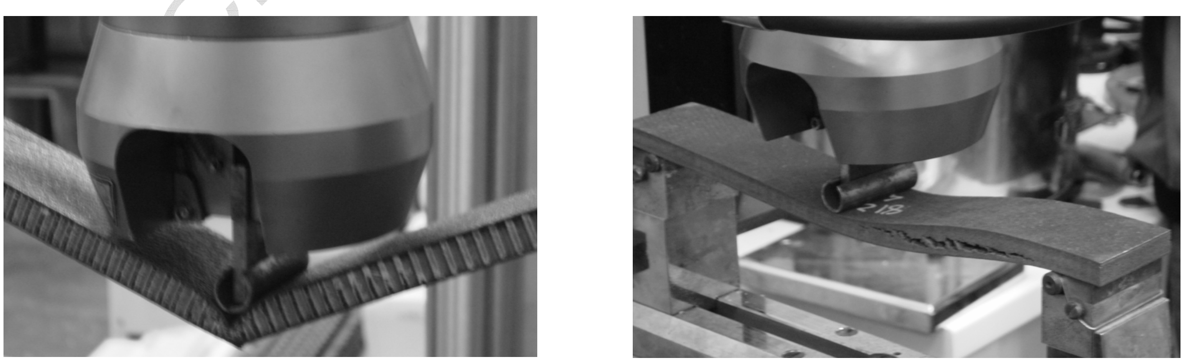
Additionally, cork based sandwich specimens present a less sudden total fracture after the yielding limit of the material has been reached. This behaviour is a good indicator of the high damage tolerance of cork composites comparatively with other core materials, which is an important issue when electing the proper materials for damage tolerant structures.



(a) (b)

(c) (d)

Figure 5 – Force-displacement curves for four different core materials: (a) Nomex honeycomb; (b) commercial cork agglomerate (ref. 8123); (c) carbon-epoxy agglomerate (2/3 granule size); (d) carbon-epoxy agglomerate (Mixed)



(a) (b)

Figure 6 – Failure mechanisms under flexural testing; (a): carbon/Nomex®; (b): carbon/cork agglomerate.

Table 5. Maximum core shear stress and face bending stress (average values)

Core material reference	τ_{max} [MPa]	Standard deviation (τ_{max})	σ_{max} [MPa]	Standard deviation (σ_{max})
Rohacell® 71 WF	0.6007	0.1617	62.38	16.79
Nomex®	0.9423	0.0307	97.86	3.19
8123	0.2332	0.0144	24.22	1.50
8810	0.1343	0.020	13.95	0.21
8303	0.1301	0.0124	13.51	1.29
2/3	0.8476	0.0151	48.90	0.87
3/4	0.9365	0.0154	54.03	0.89
Mixed	0.8325	0.0225	48.03	1.30

Table 6. Panel shear rigidity (average values)

Core material reference	U [N]	Standard deviation (U)
Rohacell® 71 WF	10 255.18	1494.66
Nomex®	19 489.52	355.46
8123	2213.80	92.34
8810	2509.86	94.72
8303	2272.49	102.24
2/3	5438.29	431.83
3/4	5893.12	267.16
Mixed	6139.31	269.31

3.2 Impact tests

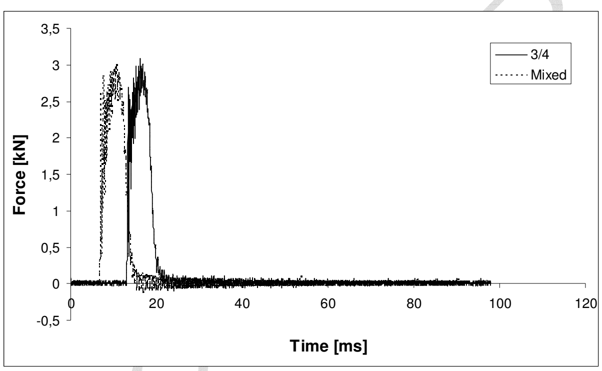
Table 7 presents the average specimen mass values and the impactor mass/specimen mass ratio, which is an important parameter in the context of impact tests since it emphasizes the impactor effect in the test results as a function of the specimen mass and dimensions. According to Olsson [17], this ratio can be used as a limiting parameter between a high velocity or a low velocity impact test.

In the force-time curves of Figures 7 and 8 we can clearly observe that sandwich panels with Rohacell® foam cores got to a maximum load peak around 2 kN, whilst all the specimens with cork agglomerate cores present load values between 2.5 and 3 kN. Comparing the impact performance of cork-epoxy and conventional cork agglomerates (Figures 7(a) and 7(b), respectively), one can see that these two types of materials have a similar behaviour, but slightly higher impact forces were obtained in the case of cork-epoxy composites.

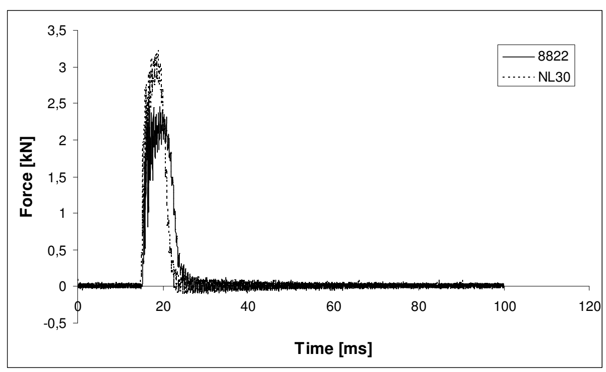
Another important remark is that the duration of the contact during impact in the case of Rohacell® cores is twice of that obtained for cork sandwich panels. This fact reveals that cork agglomerates are characterized by having a rapid response to transient loads, which added with the elastic behaviour obtained from the flexural tests can be considered as a minimizing factor concerning the probability of large extension damages.

Table 7. Average specimen mass values and impactor mass/ specimen mass ratio

Core material reference	Average mass [g]	Standard deviation (average mass)	Impactor mass/ specimen mass
2/3	227.5	2.27	13.2
3/4	229.4	0.75	13.1
Mixed	154.1	1.31	19.5
NL30	216.6	4.09	13.8
8822	149	3.89	20.1
Rohacell 71 WF	98	1.58	30.6



(a)



(b)

Figure 7 - Force-time curves for cork /carbon sandwiches; (a): cork-epoxy agglomerates; (b): conventional cork agglomerates

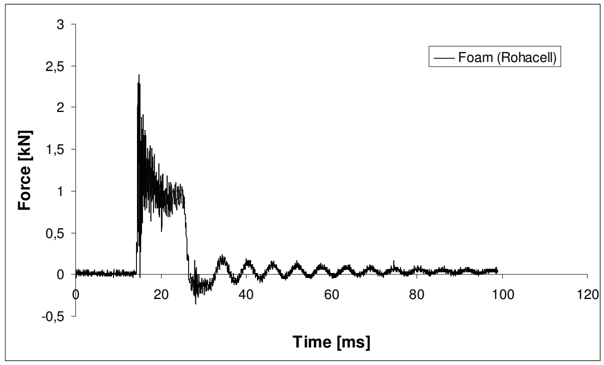
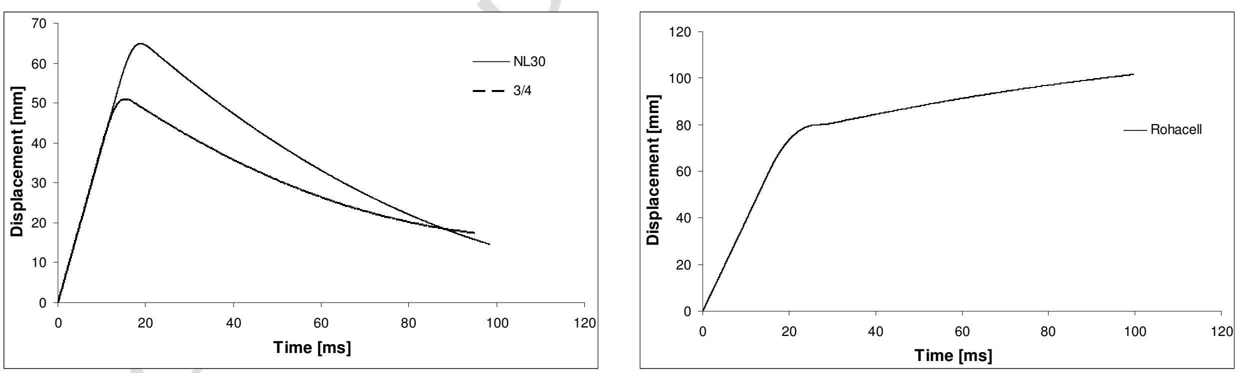


Figure 8 – Force-time curve for Rohacell®/carbon sandwiches

Regarding the displacement curves shown in Figure 9 one can observe quite different behaviours. All tests performed with both conventional and enhanced cork agglomerates (Fig. 9a) evince a decreasing displacement after impact, what means that the impactor rebounds after encountering the surface of the specimen. On the other hand, in the case of Rohacell® curves (Fig. 9b), the displacement profile progresses in an increasing mode, meaning that the impactor continues a downward movement after encountering the surface of the specimen, perforating the facesheet material and destroying the core foam. Figure 9(a) also shows that sandwich specimens with a cork-epoxy core have lower displacement levels after impact, about 25% less when compared with conventional cork agglomerates.



(a) (b)

Figure 9 – Displacement-time curves - (a) cork agglomerate/carbon sandwiches; (b) Rohacell®/carbon sandwiches

The displacement can be related with the absorbed energy by using Equation (7) and consequently different displacement curve profiles will lead to different energy curves (Figure 10). The above-mentioned decreasing displacement effect in the cork agglomerates/carbon sandwiches is reflected by the absorbed energy reduction verified in the energy curve. The energy levels inherent to both materials are the same because it follows from Equation (5) that impact tests performed with same impactor mass, velocity and from the same drop height will result in equal impact energy values.

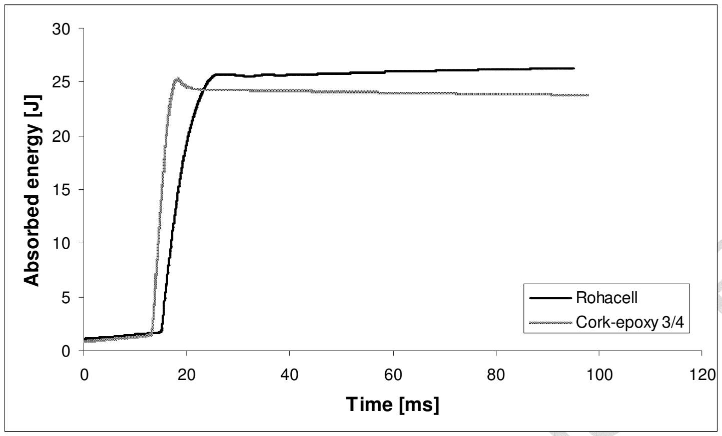
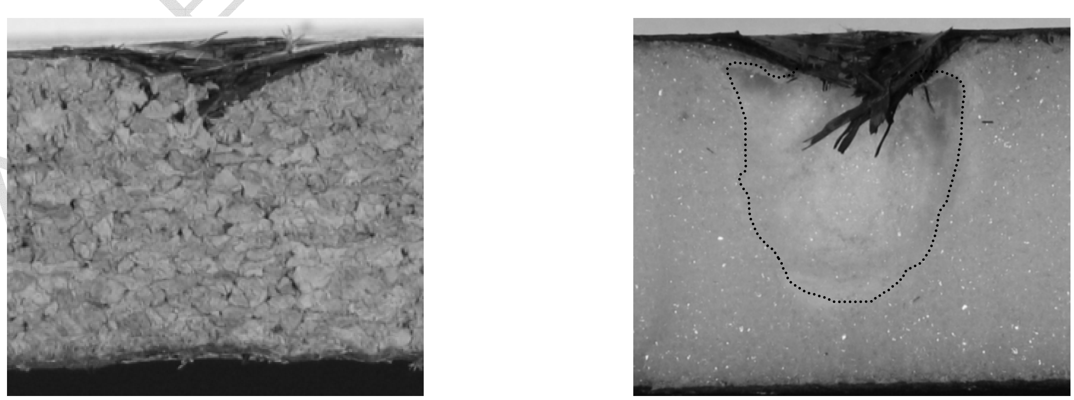


Figure 10 – Absorbed energy-time curve for 3/4 cork agglomerate/carbon sandwiches and Rohacell®/carbon sandwiches

By analysing the affected zones of the two types of materials a complementary visual damage evaluation was made (via microscopic observations). From the images in Figure 11 it is possible to infer that Rohacell®/carbon sandwiches absorb almost all the energy resulting from impact, leading to a deep perforation affecting the face sheet and also a considerable extension of damage within the core material (indicated in image (b) with a dashed contour mark). Instead of perforating, cork agglomerates/carbon components were only affected by a slight superficial dimple. This fact indicates that, for structural integrity purposes, cork agglomerates appear to be the best choice as a core material for sandwich components subjected to dynamic loading (as those resulting from impact)



(a) (b)

Figure 11 – Transversal section view of the damaged zone: (a) - cork agglomerate/carbon specimen; (b) - Rohacell®/carbon specimen

3.3 Thermal conductivity analysis

The results obtained from the thermal conductivity analysis described in section 2, and which are summarized in Table 8, allow to conclude that cork agglomerates have slightly lower values when compared with Rohacell®, but can compete with other types of foam materials normally used due to their good thermal insulating properties (such as Klegecell® R260 and Divinycell® H250). In fact, cork/epoxy agglomerates present similar thermal conductivity values when compared with these two types of foams but, in the particular case of Mixed agglomerates, these good thermal insulating properties are followed by a lower value of the density of the material, which is a interesting advantage when electing cork core materials for specific applications implying low weight requirements (such as aerospace components).

Table 8. Comparison of thermal conductivity values for different core materials.

Core Material	Mixed (Cork)	2/3 (Cork)	Rohacell® 71 WF	Klegecell® R 260	Divinycell® H250
Density [kg/m^3]	162	272	75	200	250
Thermal conductivity [W/mK]	0.045	0.047	0.03	0.042	0.046

4. Conclusions

This investigation aimed to develop cork agglomerates with enhanced mechanical properties and to evaluate their performance when integrated as core materials in sandwich structures. Cork agglomerates with enhanced mechanical performance were fabricated with epoxy resin, and their main properties were compared with both conventional cork agglomerates and high strength core materials usually used in sandwich components for transport applications.

From the results in three-point bending tests some conclusions can be withdrawn:

- There is not a clear effect of the cork granule size on the core shear stress and face bending stress obtained for the different types of cork agglomerates;
- When compared with other core materials, cork-epoxy agglomerates present a significantly better core shear stress limit, which reduces the crack propagation region. This important achievement can place cork-epoxy agglomerates in the leading edge of currently available materials used within sandwich structures;

The results obtained from the impact tests suggest that:

- The use of lighter cork agglomerates will not affect the maximum allowed loads related to impact. Also, all cork based sandwiches (regardless the type of granulate) presented considerably higher load values than those obtained for other type of high performance core materials;

- The excellent recovery capacity verified in the cork based sandwiches displacement curves is an exclusive and intrinsic characteristic of cork, regardless the type of cork agglomerate and fabrication method;
- Compared with high performance foams, sandwich components with optimized cork agglomerates have an high energy absorption capacity with minimum damage occurrence, resulting in better crashworthiness properties when impact loading is expected during service;

Thermal conductivity tests show that:

- Cork-epoxy agglomerates have good thermal insulating properties similar to other type of core materials;
- Cork agglomerates with lower densities present better thermal properties, which is an important issue when considering the design of mechanically efficient structures with low weight requirements (such as aerospace components).

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