This is a postprint version of the following published document:

Gómez, A., Sanchez-Saez, S. & Barbero, E. (2021). Compression impact behaviour of agglomerated cork at intermediate strain rates. *European Journal of Wood and Wood Products*, 79(2), 381–396.

DOI: [10.1007/s00107-020-01638-2](https://doi.org/10.1007/s00107-020-01638-2)

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COMPRESSION IMPACT BEHAVIOUR OF AGGLOMERATED CORK AT INTERMEDIATE STRAIN RATES

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Abstract

This work analyses the influence of intermediate strain rates, between 25 s^{-1} and 75 s^{-1} , on compressive behaviour of agglomerated cork. Quasi-static and dynamic compressive tests of an agglomerated cork with two different densities were carried out. This work complements previous research focused on higher strain rates. The influence of strain rate on less studied properties as densification strain or Poisson ratio is also studied. Digital Image Correlation (DIC) is applied in the estimation of the strain distribution in the longitudinal and transversal directions for both materials quantifying their heterogeneity through the specimen. Under the studied dynamic conditions, no significant influence of strain rate has been found in the mechanical properties. Young modulus, plateau stress, and Poisson ratio are higher in the densest agglomerate, whereas the densification strain is similar in both material densities. Differences in properties such as Young's modulus, Poisson ratio, plateau stress, and densification strain have been found between quasi-static and dynamic conditions for both agglomerates. In the agglomerate with the lowest density, all properties are higher in dynamic conditions than in quasi-static conditions. In the material with the highest density, Young modulus and plateau stress increase significantly, whereas the Poisson ratio decrease.

Keywords: Agglomerated cork, dynamic properties, DIC, compression

1. Introduction

Polymer cellular materials are widely used in several industries such as the aerospace, automotive, and wind energy due to its low relative density and its excellent properties (Kausar 2018; Rajput 2019). They can be found as a core in sandwich structures or as thermal, electrical and acoustic insulators. However, the inconvenience of their disposal methods (landfill, incineration) and the limitation of current recycling techniques (energy consumption, low-value products) have increased the concern about environmental sustainability (Ashby 2012). For such a reason natural materials such as cork are potential sustainable substitutes of polymeric foams in specific applications due to its mechanical properties. (Jardin et al. 2015; Lakreb et al. 2015; Ptak et al. 2017; Lakreb et al. 2018; Sergi et al. 2019).

Cork is the bark of the oak (*quercus suber L.*), a tree that grows in Mediterranean countries such as Portugal, Spain, Italy, France and Turkey (Maderuelo 2014). It is a cellular material with polygonal structure (heptagonal, hexagonal, or pentagonal) made from thin walls analogous to the honeycomb with lateral cell walls running parallel to the radial direction of the tree (Gibson and Ashby 1997; Knapic et al. 2016). In the axial and tangential directions, cork has a cellular structure similar than a brick wall. Cork cells are closed prisms with corrugated walls with cell size in the order of 30-40 μm , smaller than most polymeric engineering foams and comparable with microporous foams (Gibson and Ashby 1997; Knapic et al. 2016). Cork is transversally isotropic therefore its mechanical properties perpendicular to the radial direction (axial and tangential) are analogous (Da Silva et al. 2005).

An alternative to the natural cork is agglomerated cork (Da Silva et al. 2005; Castro et al. 2009; Sasso et al. 2018). This material is made from triturated granules of cork mixed with a polymeric binder (as polyurethane) and cured under heat and pressure in a mould. This material has an advantage over natural cork since it uses the residuals from the production of cork items, as bottle stoppers (Pereira et al. 1994; Paiva et al. 2018). Furthermore, it can reduce the variability in characteristic properties of natural material, such as anisotropy by mixing granules with random alignment (Fernandes et al. 2015; Le Barbenchon et al. 2019). Among the properties of agglomerated cork are high deformation, low permeability, low thermal conductivity, chemical stability, good energy absorption properties, and vibration damping (Da Silva et al. 2005; Karade et al. 2006; Silva et al. 2011, Ivañez et al. 2020; Sarasini et al. 2020).

Agglomerated cork shows the well-known compressive behaviour of cellular materials, characterized by three regions in the stress-strain curve (Viot et al. 2005; Ouellet et al. 2006; Li et al. 2006; Le Barbenchon et al. 2018). At low strain, the cellular material shows an elastic behaviour. In cellular solids with closed-cell, the cell edges both bend and stretch/contract due to the presence of face membranes that also stretch increasing the axial stiffness. When the strain increases, a plateau region appears in the stress-strain curve and similar to elastomeric foams this region is governed by the cell collapse due to elastic buckling of the cell walls. For closed-cell cellular solid, there is a progressive increment in the stiffness produced by the compression of the gas inside the cells and the stretching of the face membranes (Gibson and Ashby 1997). At higher strain, an increment in the slope of the stress-strain curve occurs. This region is called densification, and the increment of the stress is given due to the contact between collapsed cells of the material.

Agglomerated cork is able to recover almost completely its initial shape after compression. This capability is associated with the large recoverable strain due to elastic cell wall buckling. Previous research (Fernandes et al. 2015; Sanchez-Saez et al. 2015a) show that agglomerated cork maintains its energy absorption capabilities under multiple impacts. This gives to agglomerated cork an advantage over rigid and semi-rigid synthetic foams in which once the elastic region is exceeded the absorbed energy is unrecoverable due to plastic dissipation and brittle fracture.

Cellular materials are used in high-performance structures for impact protection and energy absorption. In such applications they are subjected to high strain rates that depending on the kind of cellular material may affect its mechanical properties (Oullet et al. 2006). This dependency on strain rate is complex and it is related to the strain rate dependency of the material from which the foam is made as well as its cell morphology. For example, in the case of semi-rigid foams both the stiffness and strength increases with the strain rate while for elastomeric foams they are almost independent of strain rate (Gibson and Ashby 1997; Sun and Li 2018).

The strain rate dependency in cellular materials is commonly attributed to the inertial effects taking place at high strain rates where dynamic crushing increases the compression strength. Some physical mechanisms are summarized below (Gibson and Ashby 1997; Sun and Li 2018):

- Localization: Cells are more tightly compressed along with a thin layer adjacent to the loading face creating a change in the cell shape leading to local strain rates that are much

larger than the apparent strain rate.

- Micro-inertia: Micro inertia arises from the acceleration of individual cell walls and struts. This phenomenon suppresses the cell-wall buckling increasing the crushing stress. This mechanism is sensitive to the structural characteristics of the cell.
- Densification: When cells come into contact in the localization region they cause a shock that raises the stress.

Another source of strain rate sensitivity in cellular materials (particularly for open-cell foams) arises from the fluid contained inside the cell. When compressed, the fluid contained is squeezed out and work is done to force the viscous fluid through the porosity of the foam. For very fast deformations, more work is done and the pore fluid induces a strong strain rate contribution to the strength. This effect strongly depends on the size of the aperture that connects the cells and on the fluid viscosity (Gibson and Ashby 1997).

In the case of agglomerated cork previous authors have studied the compressive behaviour at the quasi-static and dynamic regime. Research by Santos et al. (2017) showed that density, grain size, and binder type might modify the mechanical properties of agglomerated cork in quasi-static compression.

Jardin et al. (2015) analysed the compressive behaviour of seven different agglomerated cork and expanded cork using a universal testing machine in static conditions. Additionally, it analyses the response of the materials under double impact using a drop weight tower with a hemispherical impactor. The results of this study show a clear correlation between the density and grain size of the material on the resulting mechanical properties. Although the aforementioned study gives clear hints about the impact behaviour of the material the results could differ from a true dynamic compression experiment due to shape of the impactor and the methodology used to estimate the stress-strain curves (accelerations measured).

Dynamic compression testing over agglomerated and micro-agglomerated cork was carried out by Gameiro et al. (2007) at strain rates from 200s^{-1} to 600s^{-1} . According to their observations, the dynamic compression shows higher plateau stress than the quasi-static case. However, there is no significant variation of the mechanical behaviour in the considered dynamic range (200s^{-1} to 600s^{-1}). A similar conclusion was obtained by Sarassini et al. (2019) for agglomerated cork for three different densities at strain rates between 90s^{-1} and 238s^{-1} . Additionally, this study found a correlation between small increments in the strain rate sensitivity and material density.

A similar analysis is carried out by Ptak et al. (2017) to analyse the crushing behaviour of

agglomerate cork but no true uniaxial compression was achieved in the tests. Relatively high energy levels were achieved, with strain rates between 85 and 225 s⁻¹.

Additionally, Santos et al. 2017 carried out a static and dynamic test (65 s⁻¹) in order to show that parameters such as grain size, binder type and quantity affect the mechanical properties of agglomerated cork.

Recent studies (Sasso et al. 2017; Sasso et al. 2018) use DIC to evaluate the actual strain distribution of agglomerated cork in dynamic compression and to compute local accelerations and inertial stresses. Additionally, heterogeneous strain distribution was found among the specimens tested. However, there is still a lack of available data for dynamic compression at strain rates lower than 90s⁻¹. Studying the behaviour of agglomerated cork at intermediate strain rates is interesting since it is representative of situations such as the impact on a helmet or the impact of fragments due to a tire explosion (Viot et al. 2005; Abrate 2011).

Most of the research work in compression of agglomerated cork (Gameiro et al. 2007; Santos et al. 2017; Sasso et al. 2017; Sasso et al. 2018; Sarassini et al. 2019; Le Barbenchon et al. 2019) has been focused on the longitudinal behaviour while there is still little knowledge in its behaviour in the transversal direction and particularly in the Poisson effect. Some authors assure that the Poisson ratio in quasi-static conditions is near zero or have a constant value (Gameiro et al. 2007; Gibson and Ashby 1997; Le Barbenchon et al. 2019). Other experiments carried out over agglomerated cork of different densities agree that there is a dependency between the Poisson ratio and the applied strain in static conditions (Jardin et al. 2015).

The purpose of this work is to study the mechanical response of agglomerated cork with two different densities subjected to quasi-static and dynamic compression at several strain rates (from 25 to 75 s⁻¹), which complements the works of other authors at higher strain rates. The effect of strain rate is assessed in the global response (force-displacement curve, maximum force, absorbed energy and maximum displacement) and the mechanical properties are determined (Young modulus, plateau stress, Poisson ratio, and densification strain). The deformation field is measured through the specimen using Digital Image Correlation (DIC) in order to obtain the strain field in the longitudinal and transversal direction, allowing the estimation of the Poisson ratio. Special attention is given to this property and how it varies when the applied strain increase. The obtained data is necessary for the future implementation of numerical models related to the compressive behaviour of agglomerated cork at the studied strain rate range.

2. Materials and Methods

2.1 Materials

Compression tests were carried out on agglomerated cork with two densities, NL-10 (average density $\rho=170 \text{ Kg/m}^3$) and NL-20 (average density $\rho=215 \text{ Kg/m}^3$), manufactured by Amorim Cork Composites under the commercial name of CORKCORE. These materials are made from cork granules agglomerated with a polyurethane binder. A visual inspection of both agglomerated corks shows a heterogeneous distribution of amorphous granules. Surface analysis is conducted to determine the average size of the granules in each agglomerated cork. Due to its amorphous geometry, the average characteristic length of each granule is estimated from the projected area. From Figure 1 it can be noticed that the size of the granules is smaller for the NL-10 than for NL-20 with an average length of 1.7 mm for the NL-10 and 2 mm for the NL-20. The standard deviation is relatively large for both agglomerated being 0.5mm and 0.7mm for the NL-10 and NL-20 respectively. A comparison in the statistical distribution of the average length is shown in Figure 1.c.

c)

Figure 1. Granules in the agglomerated corks used in this work a) NL-10, b) NL-20, c) Statistical distribution of the granulate length.

The geometry of the specimens was the same for quasi-static and dynamic testing: $40 \times 40 \times 35 \text{ mm}^3$. The specimen size is one order of magnitude larger than the cork granules ensuring that the heterogeneity of the material is averaged. Three specimens were tested for each material and test condition. All specimens were manufactured from the same batch and all tests were carried out under the same conditions of humidity and temperature.

2.2. Quasi-static compression tests procedure

Quasi-static (QS) compression tests were carried out at a speed of 5 mm/min (equivalent to a strain rate: $2.38 \times 10^{-3} \text{ s}^{-1}$) using an INSTRON 8516 universal testing machine. From each test, a record of force versus displacement was obtained. The load is measured with a load cell of 5 kN while the machine crosshead displacement sensor is used to measure the applied displacement. A digital camera recorded each test at 10 fps. The video frames were used later to estimate the lateral strain using DIC.

2.3. Dynamic compression tests procedure

The dynamic compression tests were performed at different impact energies (10 J, 20 J, 30 J, 40 J, 50 J, 60 J, 70 J, 86 J) using a Ceast-Fractovis 6785 drop-weight testing machine. The impactor used was cylindrical with a mass of 9.134 kg and a flat impact surface of 50 mm in diameter. The test specimens were simply supported on the bottom surface. Impact velocities range from 1.4 m/s to 4.3 m/s, reaching average strain rates from 25 s⁻¹ to 85 s⁻¹. A PHOTRON FASTCAM SA-Z high-speed camera was used to record the testing at 2000fps.

The contact force between the impactor and specimen was measured through a dynamic digital acquisition system (DAS4000) recording data with a sample time of 9 µs. This instrumented impactor measures the contact force indirectly through the deformation of a calibrated strain gauge located in the impactor rod. Each specimen received a single impact and rebound was prevented by an anti-rebound system. The impact velocity was measured using two laser position detectors located before the impact takes place. From this initial velocity and the force record, the impactor displacement and energy can be calculated by an integration process.

From the contact force record, $F(t)$, the acceleration of the impactor, $a(t)$, can be calculated by a simple dynamic equilibrium equation, Eq. 1:

$$a(t) = \frac{F(t) - mg}{m} \quad (1)$$

Where m is the impactor mass and g is the gravity acceleration.

By integration of Eq.1, the impactor velocity can be estimated, Eq.2

$$v(t) = v_0 - \int_0^t \frac{F(t) - mg}{m} dt \quad (2)$$

Where v_0 is the impact velocity.

By another integration, the displacement of the end of the impactor, $\delta(t)$, is calculated, Eq.3.

$$\delta(t) = \delta_0 + \int_0^t \left[v_0 - \int_0^t \frac{F(t) - mg}{m} dt \right] dt \quad (3)$$

For convenience, the initial contact between the impactor and the specimen is used as a reference to estimate the impactor's displacement (and thus δ_0 is zero).

Assuming that the impactor and the specimen are in contact during the entire impact event, the velocity and displacement (calculated from Eq.2 and Eq.3) can be assumed to be equal to the velocity and displacement of the upper surface of the specimen.

The absorbed energy is estimated by the numerical integration of the force-displacement curve. This energy at an instant of time t (Eq. 4), is equal to the work done by the contact force during the loading and unloading process:

$$E(t) = \int_0^t F(t) \left[v_0 - \int_0^t \frac{F(t) - mg}{m} dt \right] dt \quad (4)$$

Since the method for estimating the absorbed energy requires the impact velocity as initial data, it is relevant to determine the accuracy of the velocity measurement provided by the data acquisition system of the drop weight tower. For this reason, the impact velocity and the residual velocity after impact were measured using an automated image tracking software and the video frames from the high-speed camera. Figure 2 shows an example of the displacement and velocity history estimated by both techniques. A good correlation between both techniques is found.

a)

b)

Figure 2. Dynamic compression test of NL-20 at 20 J. Data estimated from the data acquisition system of the drop weight tower and the tracking software. a) Impactor displacement history and b) impactor velocity history.

Although the velocity history measured by the tracking system has a high degree of noise due to the image identification algorithm it is possible to obtain the initial impact velocity by averaging the velocity in the region before the impact. Figure 3 shows the comparison in the impact velocity measured by the laser detector of the drop weight tower and the tracking system for NL-20 agglomerated cork. It can be noticed that there is a good agreement between the measurements obtained by both methods showing a relative error of 3.6% in the worst scenario.

Figure 3. Dynamic compression tests of NL-20. Impact velocity estimated from the data acquisition system of the drop weight tower and the tracking software.

2.4. Digital Image Correlation procedure

2D Digital Image Correlation (DIC) is applied to obtain the longitudinal and transversal strain distribution in each specimen point during the tests. This method provides accurate identification of changes among the video frames taken in the test correlating them at the pixel and subset level in order to find the displacement and strain field.

The lateral surface of all specimens was marked with a random black dot speckle pattern using a fine marker pen with an approximate feature size of 1mm. No white background was applied since the natural granulate texture of the material provides additional randomness to the speckle as well as enough contrast to allow correlation.

The software used in this analysis is VIC-2D (Version 6.0.6) developed by Correlated Solutions Inc. The subset size is chosen depending on the speckle size, ensuring that at least three speckle features are covered by a single subset (Figure 4). Additionally, the step size is chosen to compromise enough spatial resolution and low computational time. The difference in the image size between the quasi-static frames (2048 x 1536 pixels) and the dynamic frames (1024 x 1024 pixels) requires that both tests are evaluated with different subset and step sizes. In the case of quasi-static compression, a subset size of 81 pixels and a step size of 5 pixels are used. For the

dynamic tests, the subset size is 39 pixels while a step size is 4 pixels. With this subset size, match confidence of 0.01 pixels is achieved.

Figure 4. Speckle pattern and DIC grid size

2.5 Data reduction method

From each test, both in static and dynamic conditions, a record of force versus displacement was obtained. These curves allow the estimations of some material parameters as Young modulus, plateau stress, densification strain, and maximum efficiency. Additionally, the Poisson ratio was obtained from the longitudinal and transversal strains measured by DIC.

In the stress-strain curves, the linear-elastic region can be estimated accurately by a linear fitting curve until 4% applied strain. Therefore, the Young modulus for each test can be computed from the slope of the linear function. It is also customary in cellular materials to provide a stress value in the plateau region at 20% strain that allows direct comparison of the plateau stress of different materials or test conditions.

Densification strain is the level of applied strain where densification of a cellular material starts. To identify the onset of densification from the force-displacement curves several approaches can be used (Gibson and Ashby 1997; Avalor et al. 2001; Chan and Xie 2003; Li et al. 2006). The method based on the evolution of the energy absorption efficiency (η) is an unambiguous method to determine the transition between the plateau and densification region (Avalor et al. 2001; Belingardi et al. 2002). The efficiency can be defined as Eq.5.

$$\eta = \frac{1}{F(\delta)} \left(\frac{1}{h_0} \right) \int_0^\delta F(\delta) d\delta \quad (5)$$

Where $\mathbf{F}$ is the contact load, $\mathbf{h_0}$ is the specimen thickness, and δ is the displacement.

The maximum efficiency is estimated as the maximum numerical value in the efficiency vs displacement plot during the loading phase

From the specimen's velocity (Eq.2), the strain rate can be estimated. As can be seen in Figure 5, the instantaneous velocity varies during a test and therefore the strain rate is not constant. In the agglomerated corks studied in this work, the drop in velocity is small in a broad range of strain. For example, at 20% applied strain the velocity drop is smaller than 5% for both materials. Even at very high-applied strains such as the densification strain, the velocity drop is close to 18% for the NL-10 and 26% for the NL-20.

To allow direct comparison among different tests, an average strain rate is defined for each impact energy. This strain rate is calculated based on the average of the impact velocity and the velocity of the impactor at the maximum impact force. This method is considered the most realistic to estimate the strain rate if compared with other alternatives as using the impact velocity as suggested in other works (Avalor et al. 2001).

Figure 5. Instantaneous velocity of the impactor vs. displacement. NL-10. Impact energy: 86J

The Poisson ratio was estimated from the longitudinal strain and the lateral strain measured by DIC. From DIC measurements, a non-uniform distribution in the strain field in the test specimens was observed for both materials. Figure 6 and Figure 7 shows the variation in the longitudinal strain ϵ_{yy} and lateral strain ϵ_{xx} at different points in the specimen for quasi-static compression and dynamic compression at 40 J, and 70 J.

Figure 6. Longitudinal local strain of NL-20 at different impact energies (mean longitudinal strain 20%). a) Quasi-static, b) 40 J, c) 70 J.

Figure 7. Lateral local strain from DIC analysis of NL-10 under a 50J impact. a) 5% longitudinal strain, b) 10% longitudinal strain, c) 30% longitudinal strain.

The strain at a given point or local strain (ϵ_{yy} and ϵ_{xx}) is obtained from the DIC analysis as the ratio of the local displacement to the initial dimensions of the test specimen ($\epsilon_{yy} = \Delta y/h_0$ and $\epsilon_{xx} = \Delta x/w_0$), where Δy and Δx are the longitudinal and transversal displacement of each point, h_0 is the initial thickness and w_0 is the initial width. The axes used to define these strains are shown in Figure 6 and Figure 7. However, due to the anisotropy of the material, it is convenient to estimate a mean longitudinal strain for the whole specimen ($\bar{\epsilon}_{yy}$). The mean strain is calculated as the average value considering all points inside the specimen. The mean Poisson ratio is estimated from the mean longitudinal strain ($\bar{\epsilon}_{yy}$) and mean lateral strain ($\bar{\epsilon}_{xx}$).

3. Results and discussion

Strain rates between 25 s^{-1} and 75 s^{-1} were achieved during the dynamic compression testing using the drop weight tower. The relation between impact energy and average strain rate is shown in Figure 8. There is a linear relationship between strain rate and impact energy in both agglomerated corks at low impact energies when the materials do not achieve densification. The slope of the fitting is very similar, being in the NL-20 a 1.79% higher than in NL-10, thus no significant influence of density was found in the relationship between strain rate and impact energy. When the densification is achieved, a loss of linearity is observed in both materials.

Figure 5. Average strain rate vs impact energy

The force-displacement curves (Figure 6 and Figure 7) show the typical behaviour of cellular materials with closed cells characterized by a non-constant plateau region that slightly increase until reaching densification. It can be noticed that there is a considerable difference in the curves for quasi-static and dynamic conditions, a behaviour well-identified in previous research (Gameiro et al. 2007; Santos et al. 2017; Sasso et al. 2017; Sasso et al. 2018; Sarassini et al. 2019). The force-displacement relationship is almost the same for all dynamic cases at small strain ($< 7\text{mm}$ or 20% strain) despite the variation in the impact energy and strain rate. Since the strain rate is the highest at small deformations, no significant influence of strain rate in the mechanical properties in a range of 25s^{-1} to 75s^{-1} were observed. This complements previous observations in (Sasso et al. 2018) where it is shown that there is not considerable strain rate

sensitivity in the range between 90s^{-1} and 400s^{-1} . Additionally, this confirms the results in (Gameiro et al. 2007) where it is found a no strain-rate dependency in the plateau region for different types of agglomerated cork with different densities.

From the discharge region of the curve, it is noticed that although most of the material presents immediate elastic recovery there is certain remaining deformation after impact. This remaining deformation can be associated with permanent strains due to damage and delayed strains due to viscoelastic effects (creeping).

It is also noticed that NL-20 has higher strength and stiffness than NL-10 for both quasi-static and dynamic compression. Similar behaviour has been previously observed for pure cork and polymeric foams (Viot et al. 2005; Anjos et al. 2014).

Figure 6. Agglomerated cork NL-10. Force vs displacement.

Figure 7. Agglomerated cork NL-20. Force vs. displacement impactor.

Figure 8 plots the energy absorption efficiency vs displacement for both materials at quasi-static and dynamic compression. It is observed that η increases with deformation reaching a maximum value ($\eta_{\max}$) at the densification onset. These curves are different from those of polymeric foam, due to the existence of a more constant stress plateau in those materials.

In specimens impacted at energies of 40J for NL-10 and 60J for NL-20, no densification was observed. When a specimen is impacted at higher energies, contact between some of the cell walls of the cork granules initiates and densification begins. By increasing the impact energy, a greater strain is achieved, and a greater number of walls come into contact.

The maximum efficiency is estimated as the maximum numerical value in the efficiency vs displacement plot during the loading phase (Figure 8). At quasi-static compression, both materials show a maximum efficiency close to 0.29 with densification at 57% strain for the NL-10 and 54% strain for the NL-20 (Table 1). In dynamic compression, for impact energies that produce densification, a slight swift in the densification onset was observed. In dynamic

conditions, densification takes place at 60% strain for the NL-10 and 57% strain for NL-20, this implies an increase of 4.2% in NL-10 and of 4.4% in NL-20. Despite the difference in density (from 170 kg/m³ to 215 kg/m³), there is only a slight difference in the onset of densification for both materials, around 5%. This small dependency on density can be explained since densification onset is mostly dependent on the cell's geometry (porosity) which is similar for both agglomerates. The above bearing in mind that differences in density in agglomerated cork are created by the amount of binder used and not by the change in the porosity as in a conventional synthetic foam.

Figure 8. Energy absorption efficiency vs displacement at static and dynamic conditions: a) NL-10, b) NL-20.

From the force-displacement curves (Figures 9 and 10), the maximum contact force, absorbed energy and maximum displacement were calculated.

The maximum contact force at different impact energies for both agglomerated corks increases linearly with impact energies before densification takes place (Figure 9). For high impact energies where densification takes place, there is a sharp increase in the impact force. The loss of linearity is observed in impact energies for which the maximum strain that appears produces a large number of contacts between cell walls.

Figure 9. Maximum force vs impact energy.

Considering that the velocity and displacement measurements obtained by the acquisition system are accurate enough (as demonstrated in the previous section), the absorbed energy was determined from the kinetic energy after impact calculated by numerical integration of the force vs. displacement curve. The remaining kinetic energy obtained by the numerical integration was compared with the kinetic energy measured with the image track obtaining a good correlation between the two techniques.

From Figure 10.a it is noticed that the absorbed energy in the analysed range shows a positive linear correlation with the impact energy showing a similar curve slope for both materials. Also, the ratio between absorbed energy and impact energy was calculated (Figure 10.b). This curve shows that both agglomerated corks are able to absorb from 77% to 99% of the initial

impact energy. This figure also shows that the energy absorption ratio is slightly higher for the NL-10 than NL-20. This difference can vary from 1% up to 13%.

a)

b)

Figure 10. a) Absorbed energy vs impact energy. b) Energy dissipated ratio

Figure 11. Maximum displacement vs impact energy.

The maximum displacement for the same energy level is higher in the less dense material (NL-10) as shown in Figure 11. It can be also noticed that there is a quadratic correlation between the maximum displacement and the impact energy across the entire range of impact energies. For energies that do not produce densification in both materials, there is a clear linear trend. This behaviour is similar to that observed with force.

From the force-displacement curves (Figure 6 and Figure 7) obtained from the drop weight tower and the longitudinal and transversal strains measured from the video using the DIC software, the mechanical properties of both cork agglomerates were estimated.

Table 1 shows a summary of some mechanical properties at quasi-static and dynamic compression. Due to the variability in the mechanical properties, it is convenient to present mean values of each property with their corresponding relative standard error (RSE)

The less-dense material presents a lower Young modulus and stress plateau, both in static and dynamic conditions. This variation has been previously reported by Jardin et al. (2015), but in dynamic tests with a semi-spherical impactor. The Young modulus increases 62% in static conditions and 61% in dynamic conditions. The increment of the stress plateau is 56% and 58% respectively. By contrast, the increment of density between NL-10 and NL-20 is 26.5%. The variation in the densification strain is different, the NL-20 agglomerated cork shows a slightly lower densification strain, both in dynamic and static conditions.

A significant variation between static and dynamic properties was found in both materials, for example, an increment of 40% in Young modulus is observed in NL-10. Similar behaviour is observed in plateau stress and Poisson ratio at 1% strain. In both materials, no relevant influence of strain rate, in the range analysed, was found in all mechanical properties. The observed variation of mechanical properties with strain rate in both agglomerated cork has been found in some high-density PU foam and others such as EPS and HDPE (Ouellet et al. 2006).

Previous to the analysis of the evolution of Poisson ratio during the test, an analysis of the variation of local longitudinal strain in all points of the specimens were carried out. Figure 15 shows, as an example, the evolution of the longitudinal strain for the NL20 material in static and dynamic conditions (only three impact energies are shown for the sake of simplicity).

From these curves, it is possible to quantify the level of heterogeneity in a specimen during quasi-static and dynamic compression at the different strain levels. The vertical axis shows the range on the local strains ε_{yy} encountered inside the specimen whilst the horizontal axis shows the mean strain $\bar{\varepsilon}_{yy}$ of the whole specimen. It is clear from this figure that the local strain along the specimen can differ significantly from the mean strain value showing a relative difference from 23% up to 36% for the dynamic test and variations up to 70% for the quasi-static test.

There is a considerable difference in the strain at different points in the specimen what clearly shows the heterogeneity of agglomerated cork at a small scale. This variation could be attributed among others to the amorphous shape and random allocation of the granules as observed in the surface analysis. Additionally, the random alignment of each granule, as well as the orthotropic nature of the pure cork, could provide an additional source of variability in the local response of the agglomerate. Another possible contribution to this variability could be the presence of voids or regions of rich binder content. However, more detailed analysis at the micro-scale and mesoscale level is required and such analysis is beyond the scope of the current study. This non-uniformity of the strain components has also been previously reported by other authors in high strain rate tests using the Split Hopkinson Bar (Sasso et al. 2018).

Figure 15. Variation on local longitudinal strain vs mean longitudinal strain (NL-20). a) QS, b) 20 J, c) 40 J, d) 70 J

Figure 12 depicts the mean compressive Poisson ratio vs longitudinal strain for different energy levels. The least-square method with a third-order polynomial is used to obtain the fitting curves. No similar curves have been found in the literature.

For both agglomerates, the Poisson ratio decays with the longitudinal strain reaching a plateau at higher strains. It is observed from Figure 12 that the plateau region occurs around 12% strain. This approximately corresponds to the beginning of the plateau region in the longitudinal force-displacement curves (Figure 6 and Figure 7) and clearly shows that the decay of the Poisson ratio is associated with cell wall buckling. A similar observation was found by Fortes and Nogueira (1989) for pure cork.

a)

b)

Figure 12. Compressive Poisson ratio. a) NL-10, b) NL-20.

The reduction in the Poisson ratio is slightly higher for the more dense agglomerated cork being 59% for NL-10 and around 77% for NL-20. For example under quasi-static compression, for the NL-10 the maximum Poisson ratio is 0.067 and the Poisson ratio in the plateau region is 0.028 while for the NL-20 those values are 0.102 and 0.023 respectively. Similar reductions in

the Poisson ratio in agglomerated cork have been previously reported by other researchers in static condition and at strain rates higher than 90 s^{-1} (Sasso et al. 2018; Jardin et al. 2015).

Under dynamic compression, agglomerated cork seems to be sensitive to strain rate. Figure 12 shows the variation of the Poisson ratio for different impact energies each of them corresponding to an average strain rate given by Figure 5. In dynamic compression, the average Poisson ratio in the plateau region for NL-10 is 0.038 while in quasi-static compression is 0.028 showing an increment of 33%. This strain rate sensitivity is also visible for the NL-20 although the effect seems less strong and predictable.

At this point, it is important to highlight that using DIC for measuring the Poisson ratio in agglomerated cork at very low applied strains and very large applied strains is a challenging task. At very low applied strains $<1\%$ the chosen subset size shows difficulties to provide enough space resolution to accurately measure the very small transversal strains. At very high applied strains ($>30\%$) the excessive distortion of the speckle pattern increases the correlation error causing high dispersion in the measured data. This limitation has been also observed by other researcher using DIC (Sasso et al, 2018).

To provide some insight into the influence of the pure cork granulates on the Poisson effect of the agglomerated cork a simple analysis is carried out. The values of quasi-static Poisson ratio obtained in this analysis for agglomerated cork are compared with those reported by Fortes and Nogueira (1989) for pure cork ($\rho=164 \text{ Kg/m}^3$) in order to find a correlation in the Poisson ratio effect of the pure material and the agglomerated one.

The direct comparison can be misleading since pure cork is transversally isotropic and agglomerated cork is composed by granules of pure cork randomly allocated and aligned. Therefore, a simplified model could provide a subject for comparison. The rule of mixtures is applied to obtain the overall Poisson ratio of a mixture of granulates of pure cork subjected to axial compression. Since axial and tangential directions are equivalent in pure cork only three fundamental orientations of the granules are considered [Radial\Non-Radial], [Non-Radial\Radial], [Non-Radial\Non-Radial], where the first direction in the brackets indicate the longitudinal orientation along the cell's axes and the second the perpendicular direction. Additionally, the cork granulates are considered to be allocated in parallel to the load direction, to have the same size and the binder effect is neglected.

Following this approach, an expression is found for the overall Poisson ratio of a mixture of pure cork granules. This expression is given by the average of the Poisson ratio of the three possible orientations.

Data from Fortes and Nogueira (1989) is used in order to calculate the overall Poisson ratio and the corresponding expression is plotted in Figure together with the experimental values obtained for agglomerated cork.

It can be observed that the overall Poisson ratio of a mixture of granules show the characteristic decay and plateau observed in the agglomerated cork, Figure 17. Additionally, it can be expected that this average value represents an upper boundary for Poisson ratio in agglomerated cork since the Poisson ratio for both agglomerated cork fall under this region. However, this statement requires further analysis with more robust micromechanical models that are beyond the scope of this study.

Figure 17. Comparison of Poisson ratio of agglomerated cork and mean Poisson ratio of pure cork

From the previous results, it can be stated that a single value for the Poisson ratio of both cork agglomerates cannot be defined. For modelling purposes, this variation of Poisson ratio with the strain has to be considered to obtain accurate results.

NL-10			
Property	Static tests	Dynamic tests	Static-dynamic

	Average	RSE	Average	RSE	variation
Young modulus E (MPa)	5.14	8.0%	7.20	6.5%	40.1%
Plateau stress (MPa) (at 20% strain)	0.463	3.2%	0.723	2.1%	56.1%
Poisson ratio (at 1% strain)	0.067	0.6%	0.102	4.9%	51.3%
Poisson ratio (at 4% strain)	0.055	2.5%	0.075	3.4%	36.6%
Poisson ratio (at 20% strain)	0.028	10.7%	0.038	5.3%	33.1%
Densification strain	0.57	0.8%	0.60	1.00%	4.2%
Maximum efficiency	0.29	0.2%	0.31	0.60%	8.6%
NL-20					
	Static tests		Dynamic tests		Static-dynamic variation
Property	Average	RSE	Average	RSE	
Young modulus E (MPa)	8.322	15.84%	11.6	4.5%	39.1%
Plateau stress (MPa) (at 20% strain)	0.722	0.66%	1.14	2.4%	58.2%
Poisson ratio (at 1% strain)	0.102	6.72%	0.077	2.6%	-24.3%
Poisson ratio (at 4% strain)	0.062	7.94%	0.059	1.5%	-5.9%
Poisson ratio (at 20% strain)	0.023	17.01%	0.023	7.1%	-0.4%
Densification strain	0.527	0.57%	0.57	1.6%	7.3%
Maximum efficiency	0.281	0.49%	0.30	0.5%	8.5%

Table 1. Summary of mechanical properties at quasi-static and dynamic compression of NL-10 and NL-20.

In the studied range of strain rates, the mechanical properties do not change significantly, although differences were observed between dynamic and static properties. These results suggest that modelling dynamic compression events with agglomerated cork requires the use of proper dynamic properties. In some scenarios where the strain rate is between 35s^{-1} and 75s^{-1} , it might not be necessary to adjust the strain rate dependency of the material model since the variation is small in this range, whenever dynamic properties are used.

4. Conclusion

Quasi-static and dynamic compression testing is carried out for an agglomerated cork with two densities using a universal testing machine and drop weight tower. Results show that there is a difference in the mechanical response under quasi-static and dynamic compression. For example, in NL-10 the increase in Young modulus, plateau stress and Poisson ratio (at 1% strain) from quasi-static to dynamic condition is higher than 40%. However, there is no significant variation in the stress-strain relationship for strain rates in the range of 25s^{-1} to 75s^{-1} . It is also noticed that NL-20 has higher strength and stiffness than NL-10 for both quasi-static and dynamic compression. It is also found that the maximum force at a given impact energy level seems to be very similar in both materials. Additionally, densification strain is also similar,

The energy dissipation of agglomerated cork is studied showing that both materials are able to dissipate from 77% to 99% of the initial impact energy in the studied energy range. The differences in densification initiation are similar for both materials, thus the increase in density does not modify the onset of densification in the same proportion.

DIC is used to analyse the strain distribution through the testing specimens. Results show that agglomerated cork is highly heterogenic at the small-scale level. Observations also show a difference in the Poisson ratio of the agglomerated cork when loaded in quasi-static and dynamic compression. The Poisson ratio (for both loading scenarios) is neither constant nor zero as suggested by previous research but decreases with longitudinal strain reaching a plateau after 12% strain. For such a reason in order to develop a numerical model of the material, it is convenient to include the Poisson ratio sensitivity on strain and strain rate.

Acknowledges

The authors acknowledge the Ministry of Economy and Competitiveness of Spain for the funds received for this work within the framework of the project DPI2017-86324-R.

Declarations

Funding

The authors acknowledge the Ministry of Economy and Competitiveness of Spain for the funds received for this work within the framework of the project DPI2017-86324-R.

Conflict of interest

On behalf of all authors, the corresponding author states that there are no conflicts of interest.

Ethics approval

Not applicable

Consent to participate

All authors has participated in the paper

Consent for publication

The manuscript has been read and approved by all authors

Availability of data and material

Not applicable. All data are included in the paper.

Code availability

Not applicable

Authors' contributions

All authors contributed to the study conception and design. Material preparation were performed by A. Gómez. Experimental tests, data collection and analysis were carried out for all authors. A. Gómez write part of the first draft of the manuscript with contributions of S. Sánchez-Sáez and E. Barbero in the results and discussion section. S. Sanchez-Sáez and E. Barbero wrote the following versions of the manuscript with contributions of A. Gómez. All authors read and approved the final manuscript.

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