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Strain-rate effect on the deformation mechanisms of agglomerated cork

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ABSTRACT

Cork is a multi-phased biosourced polymeric material. In this case study, it was agglomerated with a thermosetting resin by an uni-axial compression process. Agglomerated cork is nowadays considered for shock absorption applications. Therefore its behavior at high strain rates is of interest. The influence of the mean strain rate on the mechanical behavior of agglomerated cork and the associated strain mechanisms is studied here. Compression tests were performed in quasi-static ($\sim 4.2 \cdot 10^{-3} \text{ s}^{-1}$) and dynamic ($\sim 70 \text{ s}^{-1}$) regimes. A specific assembly, the fly wheel, made it possible to obtain an almost constant deformation rate during the test under dynamic conditions. As expected for a polymeric material, the Young's modulus of the material and the energy absorbed at densification (elastic and dissipated) during compression strongly depend on the average deformation rate. Using the correlation of digital images (DIC), the deformation mechanisms involved during the different stress regimes could be observed. Deformations which are highly heterogeneous take the form of localization bands. In quasi-static conditions, these localization bands are observed near the interfaces between grains. In a dynamic regime, however, deformations seem more diffuse.

Keywords: Dynamic loadings, Compression, Cellular materials, Cork agglomerates, DIC

INTRODUCTION

Cork is a bio-sourced material coming from the bark of the oak tree *Quercus Suberus* L.. Most of it come from Portugal [1]. Cork is a cellular material meaning it is formed by a three-dimensional network called cell walls (Fig. 1). Suberin, a polymeric substance, is the major component of cork cell wall. The others are lignin, cellulose and hemi-celluloses [2]. Because of its cellular structure, foams like cork have unusual mechanical properties: they can be stiff, yet light, and they are capable of absorbing large deflections and thus large amounts of energy [3]. Because of it, cork by-products like agglomerated cork are now being considered for impact-absorbing applications. Ranging from the container for the transport of sensible pieces to sports items and including lightweight aeronautic components, a wide range of applications is foreseen [1]. Previous works studied the fundamental aspects of the static and dynamic mechanical behavior of agglomerated cork under simple loadings [4]. For example, the strain-rate dependency of cork products was highlighted with dynamic loadings in compression [5]. Yet strain mechanisms in compression are still unclear for this this multi-scales cellular material [6,7].

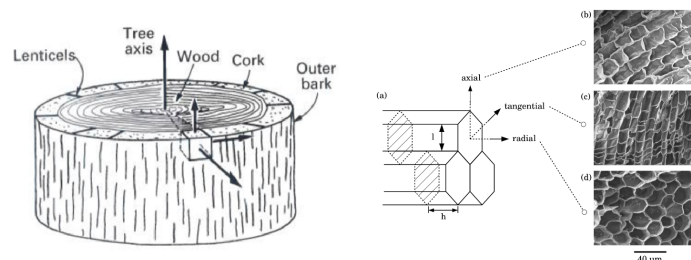


Figure 1: Structure of cork in the bark of a oak tree

BACKGROUND

Material

To obtain agglomerated cork, small beads ($\varnothing = 0.5/1$ mm) were mixed together with a bio-sourced thermoset resin reinforced with short fibres ($\varnothing = 7 \pm 2$ μm and $l = 300$ μm). It was then uniaxially compressed into a $1000 \times 500 \times 50$ mm^3 block at a 0.42 density. Resin crossing was finally made in an autoclave at 130°C during 12 hours. The resulting material can then be considered at several scales as shown in Figure 2. This compression causes geometric and mechanical anisotropy at the grain scale [7]. Figure 3 shows the two induced directions. Directions in the plane (Oxy) will be called in-plane directions and the direction (Oz) will be called off-plane direction. This article focuses on the mechanical behavior in the out-of-plane direction.

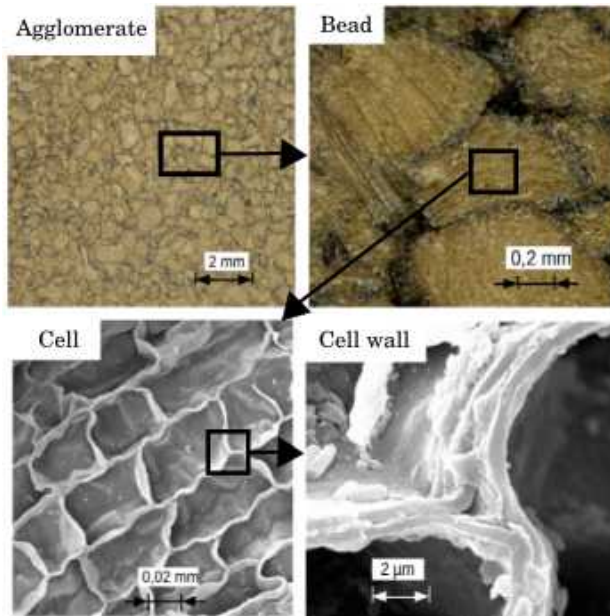


Figure 2: Different observation scales for cork agglomerates. An optical microscope was used for particle and grain scale observations. A scanning electron microscope (SEM) was used for cell-scale observations.

Microstructure characterization

In order to know the organization of the grains on the surface, the specimens were observed using a microscope optics before mechanical characterization. A Keyence microscope was used. The surface was observed and the picture resolution was around 9000×9000 pixels. The microstructure of the specimens was also observed with the EVO scanning electron microscope (SEM) Zeiss after compression. The specimens were cut with new razor blades to minimize the damage done to the cells during cutting [3]. Gold was then sputtered at the samples surface to allow their observation.

Compressive loadings at several strain-rate regimes

The specimens, previously observed under the optical microscope, were then compressed. The behavior for compression in the out-of-plane direction is presented here. In quasi-static mode, this compression was performed at $4.2 \cdot 10^{-3}$ s^{-1} using a Zwick Roell 250kN compression machine. The tests were tracked with a Canon EOS 50D camera at a frequency of 1 Hz. The definition of the pictures was 3168×4752 pixels. Local correlation of the images was then operated in order to study the strain mechanisms.

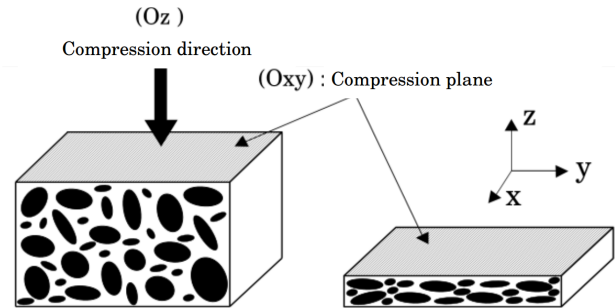


Figure 3: Scheme of the fabrication process done by uniaxial compression.

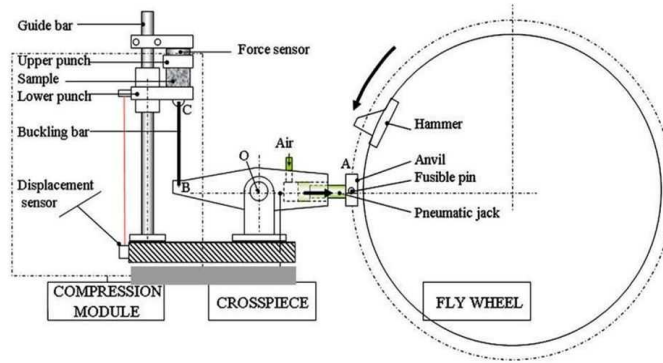


Figure 4: Fly-wheel: a set-up for compressive dynamic loading at constant strain-rates.

In order to achieve the dynamic compression speed (around 70 s^{-1}), an original set-up was used. The fly wheel, visible in Fig. 4, consists in a steel wheel with a large moment of inertia (77 kg m^2). This ensures that during loading, the strain rate is almost constant. However, the speed of unloading is not controlled. The force/displacement signals during the unloading will therefore not be studied. The tests were filmed using a fast Photron SA5 camera at a frequency of 12.5 kHz. The image resolution was 640x848 pixels. For both types of tests, the stress calculation is facilitated by the Poisson coefficient close to 0 for agglomerated cork. So we have $\sigma = F/S_0$, the nominal stress and $\epsilon = \ln(1 - L/L_0)$, the nominal deformation.

ANALYSIS

Mechanical Behavior

The compression tests provided the stress / nominal strain curves. Fig. 5(a) shows that agglomerated cork behaves like a foam in compression [3]. We can therefore distinguish three main stages during deformation. First, the specimen deforms in a linear manner, which mainly corresponds to the bending of the walls. Then the stress increases slowly for a wide range of deformation. This area is called the plateau. It corresponds to the progressive buckling of the cells. Finally, when all the cells have collapsed, the behavior of the material approaches that of a dense material. The stress therefore increases much more significantly. For compressions in quasi-static mode, the discharge was also recorded. There is a significant hysteresis. Immediately after the test, the deformation of the specimens was 0.20 ± 0.03 on average. Long after the test, this residual deformation was close to 0.05. The deformation mechanisms likely the buckling of the cell walls therefore seem to be mainly

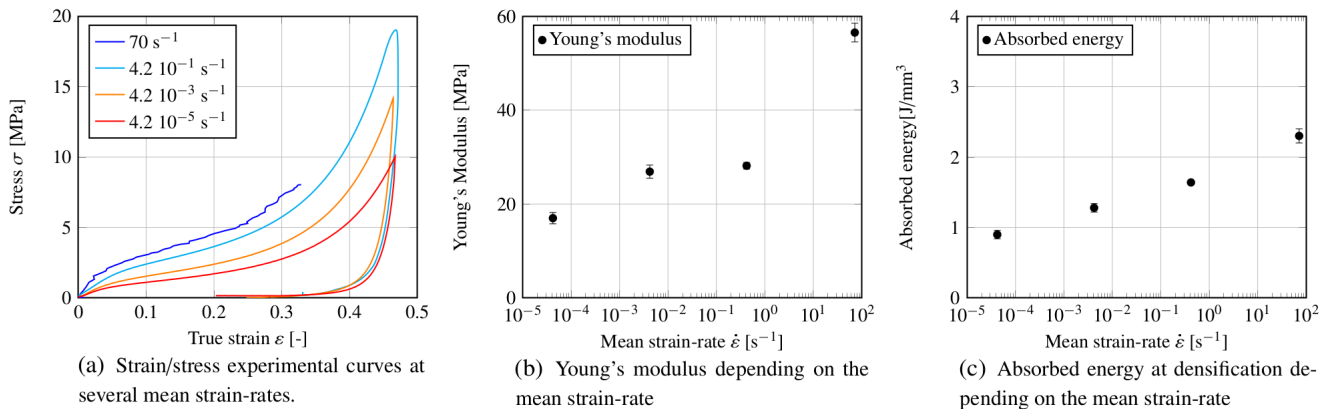


Figure 5: Experimental results of the compression tests in the out-of-plane direction at several mean strain-rates. elastic, even at high deformation rates.

From these curves, the Young's modulus (slope of the linear part, for low deformations) as well as the energy absorbed before the densification stage (dissipated and elastic) could be determined. For low speeds, the Young's modulus seems to increase slightly, linearly as a function of the decimal logarithm of the sollicitation speed. However, for the dynamic sollicitation speed, a high increase in this module is noted. On the contrary, the absorbed energy seems to increase linearly according to $\log(d\epsilon/dt)$.

The correlation of digital images shows results for the two sollicitation regimes that appear similar at the agglomerate scale (Fig. 6). For small deformations, the deformation field seems almost homogeneous. When the plateau is reached, heterogeneities in deformations begin to appear. They then develop in the form of localization strips, perpendicular to the compression direction of the test. Some discrepancies can however be noticed. For the same mean strain, localization bands seem more intense in the dynamic regime. In order to better study it, one need to look closer, at the bead scale.

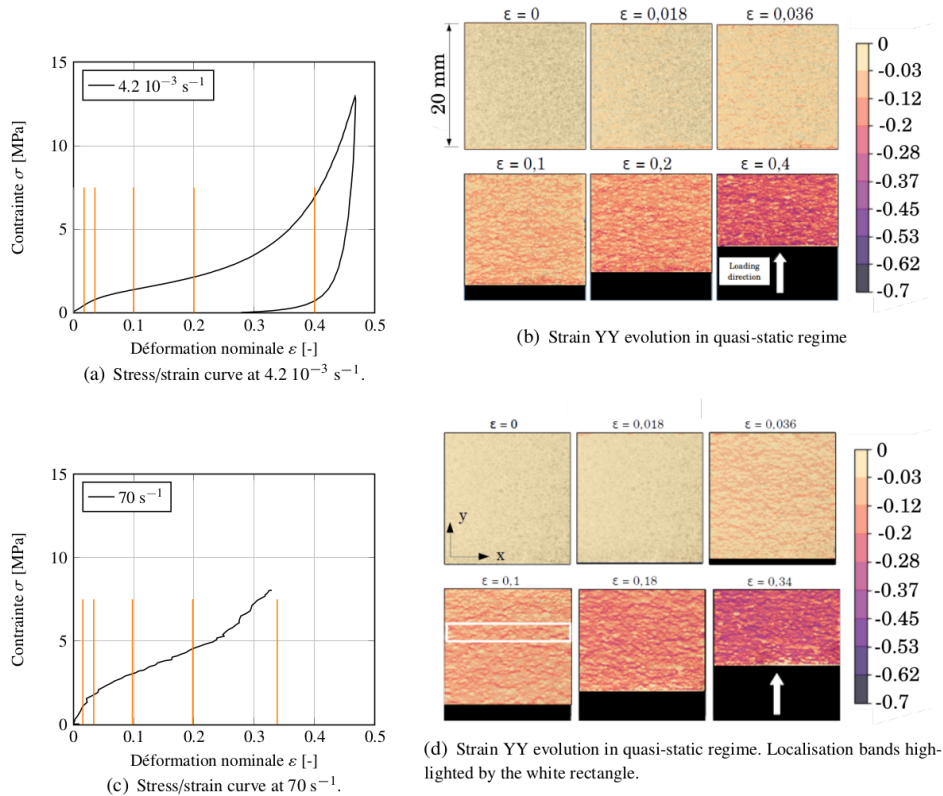


Figure 6: Chronology of deformation during a compression test at the two different stress regimes and the corresponding experimental stress/strain curves.

Microstructure influence

The superposition of the deformation maps and interfaces for quasi-static loadings is illustrated in Fig. 7. A significant localization of deformations near the interfaces can be observed. Thus, during a compression test, the localization of strains seems to begin with the stochastic buckling of cells present near the beads interfaces. This has been noticed on observations made at the SEM as shown in Figure 8. This deformation then propagates to neighboring cells also close to the interfaces. Finally, according to several criteria of shape or multi-scale structure [8], this deformation propagates to neighboring beads (in the compression plane), thus taking the form of localization bands. These bands then grow on the entire sample. For dynamic loadings, the strain appeared more homogeneous inside one bead. The result is though very dependent on the picture resolution.

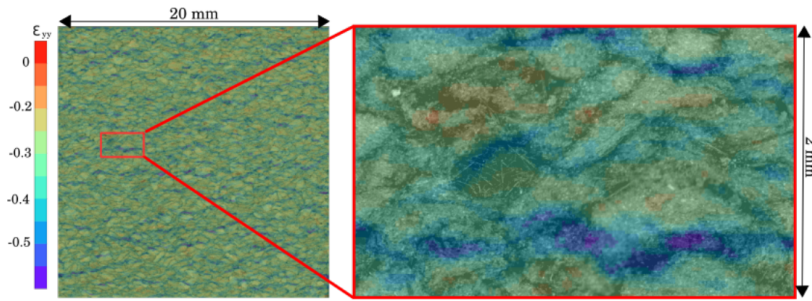


Figure 7: Superposition of the YY strain map obtained by DIC and the surface taken under an optical microscope

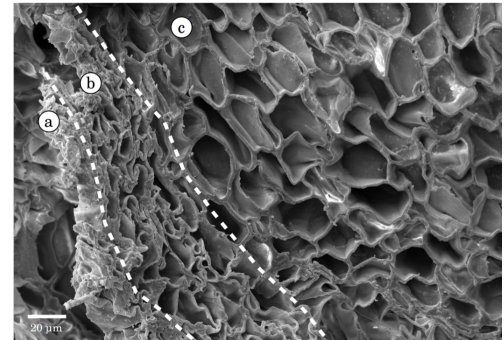


Figure 8: State of the cells at the interface between beads. Photo taken at the SEM. a) Interface. b) Collapsed cells at the interface. c) Interior of the bead.

CONCLUSION

The effect of strain-rate on the behavior and deformation mechanisms of agglomerated cork has been studied here. Intragranular observations were therefore necessary. The deformations were studied on the surface of the specimens by DIC. The specimens were compressed either in quasi-static mode (at several speeds) or in dynamic mode using the original inertial wheel assembly (around 70 s^{-1}) allowing a quasi-constant loading speed during loading. The stress/strain curves show a dependence on the strain-rate of the material. Young's modulus increases slightly with it in quasi-static mode. It then increases more abruptly under a dynamic strain-rate. The absorbed energy seems to increase linearly over the entire range of strain-rates of this study. The strain fields obtained by DIC are very heterogeneous from the plateau phase. These heterogeneities take the form of location bands perpendicular to the direction of sollicitation. In quasi-static mode, these deformations are located near the interface between two grains. Thus the deformation of the cork grains is initiated on the cells at the interface and then propagates into the neighboring cells. In dynamic these localization bands seem more intense but the strain appears more homogeneous inside one bead.

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