Materials & Design (2015). 65, 743-748.
DOI: http://dx.doi.org/10.1016/j.matdes.2014.09.054

Dynamic crushing behaviour of agglomerated cork

S. Sanchez-Saez [a,*], S.K. García-Castillo [a], E. Barbero [a], J. Cirne [b]
[a] Department of Continuum Mechanics and Structural Analysis, University Carlos III of Madrid, Avda. de la Universidad 30, 28911 Leganés, Madrid, Spain
[b] Structural Integrity Group, Mechanical Engineering Department, University of Coimbra, 3030-788 Coimbra, Portugal
* Corresponding author. Tel.: +34 916248882. E-mail address: ssanchez@ing.uc3m.es (S. Sanchez-Saez).

Abstract - For reasons of energy saving and pollution reduction, there is a growing interest in the development of lightweight structures manufactured with materials of natural origin and recyclable. Agglomerated cork is a mixture of natural cork and an organic binder, and can be considered an alternative to polymeric foams used in structural applications with a high capacity of energy absorption. One of these applications involves impact-absorbing elements in vehicles, which are subjected mainly to dynamic compressive loads. In this work, the dynamic crushing behaviour of agglomerated cork was experimentally studied, analysing the influence of the specimen thickness on the energy-absorption capacity, contact force, displacement, and strain. Dynamic crushing tests with specimens of four different thicknesses were performed in a drop-weight tower. An increase in the maximum contact force, displacement, and strain was observed when the impact-energy/thickness ratio increased. For each specimen thickness a linear variation of the maximum displacement and energy absorbed with the impact-energy/thickness ratio was found. It was observed that the energy absorbed by agglomerated cork did not depend on the specimen thickness, but only on the impact energy.

Keywords - Agglomerated cork, Dynamic crushing , Drop weight tower, Thickness, Absorbed energy

1. Introduction

In recent years, increasing environmental consciousness and the need for sustainable development has stirred increasing interest in the use of natural materials for the transport industry, as these materials are obtained from renewable resources and they facilitate recycling the components at the end of their service life. Therefore, these materials are undergoing increasingly wide use in semi-structural applications [1–3].

In many applications, agglomerated cork is used. This material is made from a mixture of natural cork and an organic binder that is pressed in an autoclave and crossed by a water vapour flow at high temperature. An advantage of this material is the possibility of changing its density and thus its properties, maintaining the advantages of recyclability and renewable source of raw material [4].

Agglomerated cork is a complex cellular material that has a good damage tolerance against impact loads, good thermal and acoustic insulation, and excellent damping characteristics for vibration suppression [5]. Due to these properties, cork has been used as acoustic or thermal insulation and in thermal-protection systems for spacecraft or civil construction works [6–8].

However, the mechanical behaviour of this material has not been sufficiently studied. Research on the mechanical behaviour of agglomerated cork is limited to a relatively small number of studies on static compression, tension, shear, bending, and creep, either alone [9–11], as a sandwich-core structure [12–14], ,or asa filler of a tubular structure [15,16].

Agglomerated cork is a good alternative to the use of polymeric foam in energy- absorption applications, since it has good energy-absorption capabilities and has almost total springback [4,17]. For example, if the specific compressive strength against the specific modulus is compared, cork is better than many comparable flexible polymer foams and some rigid polymer foams [13]. Today's vehicles have passenger-safety devices designed to absorb the energy due to an impact, and therefore increased attention has been focused on the crashworthiness. In these applications, a crushable material is added to the structure to increase the crushing strength and the energy-absorption capabilities [17–19].

In vehicles, the energy-absorbing elements designed to withstand frontal impact are often designed to work in compression [18]. The mechanical behaviour under quasi-static compression of the agglomerated cork is the one typical of a cellular material. Under static compressive loads agglomerated cork shows a linear elastic behaviour due to the bending resistance of the cell walls, with a plateau where the stress is almost independent of strain, due to the progressive buckling of the cells walls. This behaviour ends when the cells completely collapse, from which point a sharp increase in stress related to densification of the material occurs. This behaviour is strongly influenced by the density [9,17,20]. However, the forces that arise during a collision are dynamic, making it necessary to evaluate the behaviour of agglomerated cork under these conditions.

Some studies have analysed metal tubular structures filled with agglomerated cork subjected to low-velocity impact [15,16] and high-velocity impact [21]. However, no information about the mechanical behaviour of agglomerate cork subjected to dynamic loads is available in the literature. Therefore, to optimise the design of structures with agglomerated cork, studies are needed in order to understand the behaviour of this material under dynamic conditions.

Thus, the aim of this work is to analyse the dynamic crushing behaviour of the agglomerate cork and the influence of the material thickness in the energy-absorption capacity of a structure. Dynamic-crushing tests were performed on specimens of agglomerated cork of four different thicknesses, analysing the maximum contact force, maximum displacement and strain, and absorbed energy.

2. Material and methods

The material used was a commercial agglomerated cork manufactured by Amorin Cork Composites (NL-10). This agglomerated cork was made from a mixture of cork particles and a polymeric binder, with a density of 140 kg/m^3.

Dynamic crushing tests were performed using an instrumented drop-weight tower, CEAST Fractovis 6785 to characterise the energy-absorption behaviour of the agglomerated cork specimens. The impactor had a circular-flat tip 50 mm in diameter (Fig. 1) and a total mass of 4.134 kg. Specimens had a cross-section of 50 mm $\times$ 50 mm and four different thicknesses (15, 35, 50, and 70 mm). In all tests, the specimens were centred on a lower compression plate.

In order to evaluate the influence of the specimen thickness on the dynamic crushing behaviour of agglomerate cork, a ratio of impact-energy to thickness was defined. Several levels of impact energy were selected for each thickness to obtain the same ratios. A total of 60 specimens were tested. In Table 1, the levels of impact energy, the impact energy to thickness ratios, and the number of specimens tested for each specimen thickness are showed.

Each test provided a record of the load applied to the specimen by the impactor. The theoretical impact velocity could be estimated by the height from which the impactor is dropped. This velocity can be estimated matching the potential energy of the launching point to the kinetic energy at point of impact. Nevertheless, when the impactor reaches the specimen, the velocity is lower than the predicted one due to the friction undergone during the fall. Also, an error in measuring the dropping height causes a rough estimate of the impact velocity using this method. To obtain an estimation of impact velocity more accurate, a high-speed video camera APX PHOTRON FASTCAM was used to record the tests. A detailed comparison of both methodologies to estimate the impact velocities was carried out in [22].

The camera data-acquisition system allows up to 250,000 frames to be taken per second. For better record quality, a high-intensity light source, model ARRISUN 12 plus, was used. The impact and rebound velocities of the impactor were estimated from the record of the camera, measuring the distance travelled by the impactor in several consecutive frames. The number of frames was selected to ensure an accurate estimation of the velocity. The method is explained in more details in [23]. From these velocities, the kinetic energies of the impactor before (impact energy) and after the impact were calculated. The difference between both energies is the energy absorbed by the specimen. Also the displacement of the impactor was determined from the camera record.

Fig. 1 shows some frames of the crushing response recorded by the high-speed video camera, for a specimen of 35 mm thick impacted to 12.4 J. This figure shows the compression process of the specimen (from Fig. 1b–d), the maximum compressive displacement (Fig. 1d), and the rebound process of the impactor (from Fig. 1d–f). The specimens show an almost total springback, typical of viscoelastic materials [20], as can be seen in Fig. 1g–h.

3. Results and discussion

The contact force between the impactor and specimen, the displacement and strain of the specimen, and the absorbed energy in the crushing process were determined for the dynamic crushing tests.

In order to evaluate the influence of the specimen thickness in the dynamic crushing behaviour of agglomerate cork, the variation in the all previous variables was analysed as a function of the impact-energy to thickness ratio.

3.1. Contact force

Contact force is a relevant parameter in the study of energy-absorption elements [24]. For each test, the contact force as a function of the contact time was recorded. As an example, the contact-force curves of specimens with different thickness for impact energies around 17 J are shown in Fig. 2. All curves exhibit some oscillation due to the vibration of the testing device and specimens, as mentioned by other researchers regarding other cellular materials [25,26]. However, these oscillations were greatest for the smallest thickness studied (15 mm), possibly due to the lower damping in this specimen. Moreover, in the specimen 15 mm thick the greatest contact force was observed, as well as the lowest total contact time. The contact force decreased as the specimen thickness increased. The variation of the contact force with the thickness could be influenced by the damping of the material. Greater specimen thickness means more mass and hence greater damping, which reduces the acceleration of the impactor and thus the contact forces. Similar behaviour was observed in expanded polystyrene foam [24]. This trend was also detected for all impact energies.

In Fig. 3, as an example, the curves of the contact force vs. time were drawn for a similar ratio, about 500 J/m, for all the thicknesses studied. All force curves exhibited some oscillations, which were similar to those shown in the Fig. 2 and they had the same cause. This figure reflects that the maximum values of the forces were similar for the different thicknesses studied. However, the contact time increased with the specimen thickness.

Fig. 4 shows the maximum contact force vs. impact-energy/thickness ratio for all the tests made in this work. The maximum contact force increased with the impact-energy/thickness ratio. Although, this result showed a large dispersion, the values of maximum contact force were similar for the same impact-energy/thickness ratio and, the force increased within a linear interval of 748 N with the impact-energy/thickness ratio. The cause of this dispersion could be the natural origin of the tested materials and thus variation of properties between different samples. An additional reason for this dispersion could be the noise in the force–time record. As previously mentioned, the register of force has a high level of oscillations, particularly in the specimens of 15 mm in thickness. The presence of noise in the signal strength is very common in dynamic tests and is linked with vibrations wave

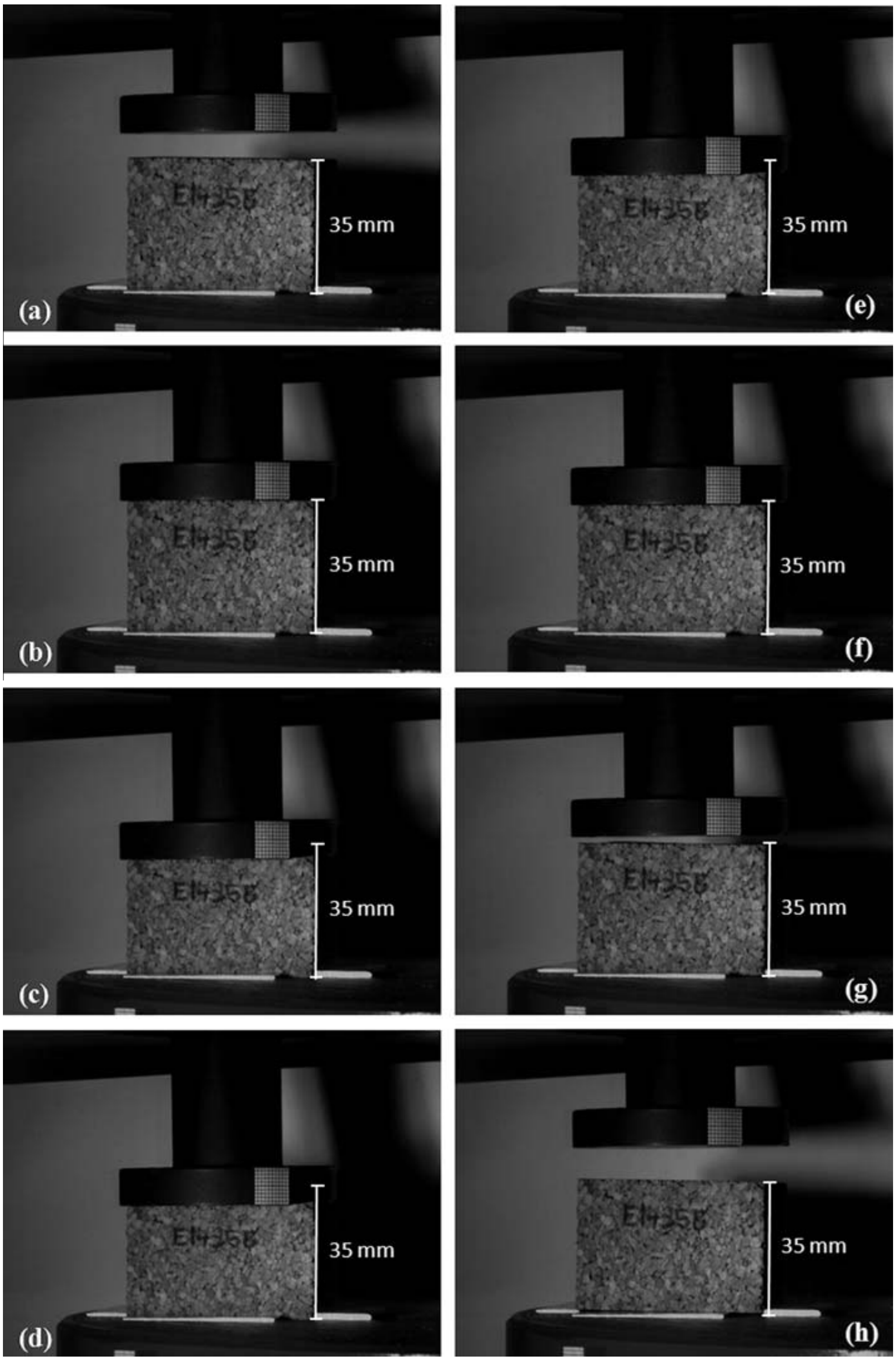

Fig. 1. Displacement of the impactor and the agglomerated cork specimen during the dynamic crushing test.

propagation through the sample and the testing machine [25]. The estimate of the maximum force is hindered by the presence of these oscillations, which causes the differences between the force values for the same test conditions increase. Agglomerate cork is an excellent vibration damper [16], so in the thinnest specimens the force oscillations are the greatest. As can be seen in Fig. 4 the highest dispersion appears in the 15 mm thick specimens.

The maximum contact force increased with the increment of the impact-energy/thickness ratio for all the specimens studied. This could have resulted because this ratio caused a larger displacement, as displayed in the Fig 5, which led to the crushing of a larger volume of the agglomerated cork and thus an increment in the maximum contact force.

3.2. Displacement and strain of the specimens

For each test, the maximum displacement was determined from the high-speed camera recordings. The maximum strain was calculated as the ratio between the maximum displacement and the specimen thickness The values of both variables (displacement and strain) exhibit a large dispersion, perhaps due to irregular cell distribution of the agglomerated cork and the natural origin of those materials.

The results of the maximum displacement vs. the impact-energy/thickness ratio are presented in Fig. 5. For each specimen thickness analysed the maximum displacement augmented when the ratio increased, and this relationship was approximated linear.

Table 1
Impact energies, impact-energy to thickness ratios, and number of specimens used in experimental tests.

Specimen thickness (mm)	Theoretical impact energy (J)	Theoretical impact-energy/ thickness ratio (J/m)	Number of tested specimens
15	6	400	4
	8.6	573	4
	10	667	2
	12	800	3
	20	1333	2
35	10	286	4
	14	400	4
	20	571	2
	23.3	666	4
	28	800	4
	40	1143	1
50	14.3	286	4
	20	400	2
	28.6	572	4
	33.3	666	4
	40	800	2
70	20	286	2
	28	400	4
	40	571	2
	46.7	667	2

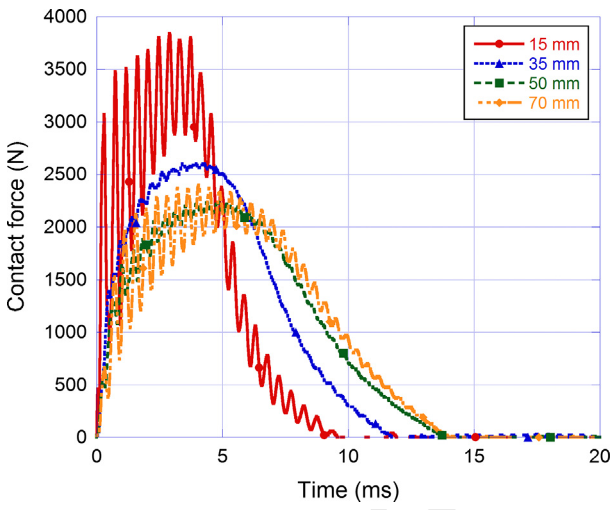

Fig. 2. Contact force vs. contact time for a dynamic crushing test at an impact energy around 17 J.

The fitting curves have different coefficients of determination R^2, between 0.6993 in the specimens 15 mm thick and 0.9090 in those 35 mm thick due to the dispersion observed in the results.

Since specimens with different thicknesses were compared, the longitudinal strain in the thickness direction was also analysed. The Fig. 6 shows the variation of the strain with the impact-energy/thickness ratio.

The longitudinal strain increases with the impact-energy/thickness ratio. The dispersion of this variable is great and therefore it is difficult to plot a fitting curve. However, the increment of the strain could augment with ratio in a linear interval of 0.139.

3.3. Absorbed energy

From the force–time curve, the energy at each instant in time was calculated by a double integration process [27]. An example of energy-time curve for an impact energy of around 17 J is given in Fig. 7. The absorbed energy was around 14 J. No significant variation in the final absorbed energy (5%) with the thickness was detected for the different thicknesses.

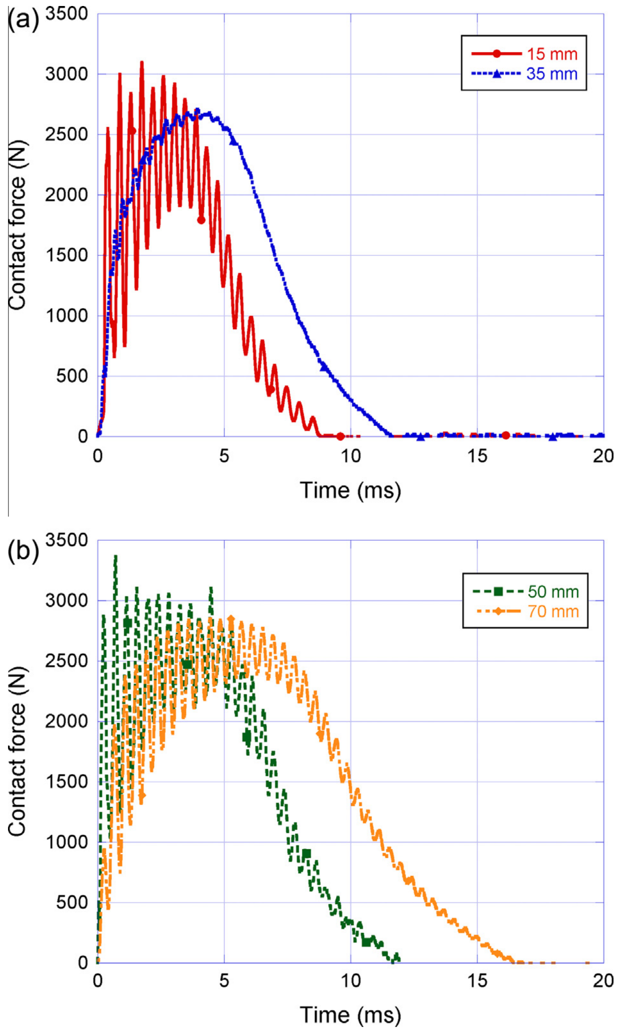

Fig. 3. Contact force vs. contact time for a dynamic crushing test at an impact-energy to thickness ratio close to 500 J/m. Specimen thickness: (a) 15 and 35 mm and (b) 50 and 70 mm.

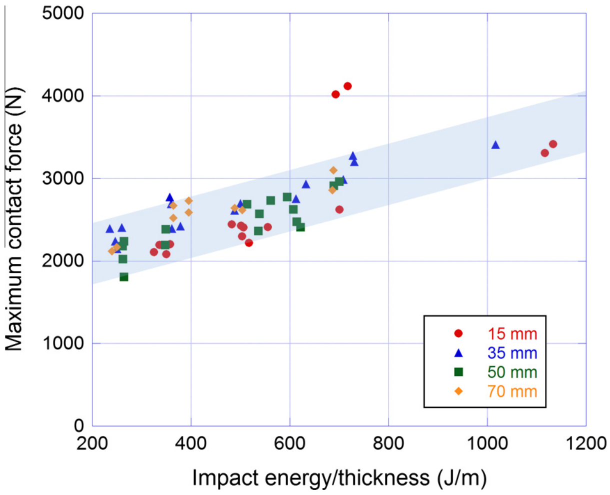

Fig. 4. Contact force vs. impact-energy/thickness ratio.

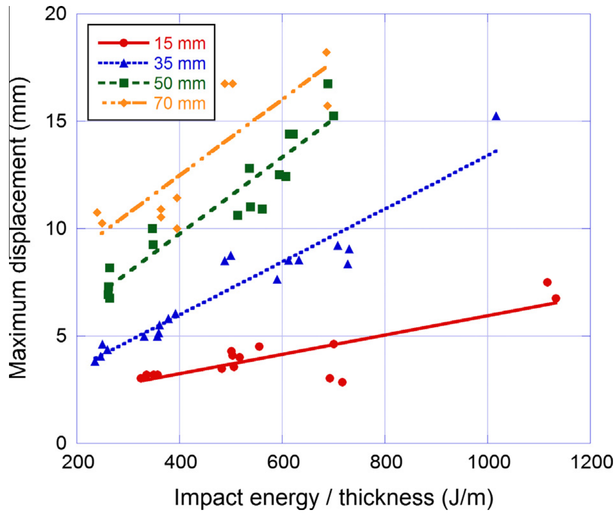

Fig. 5. Maximum displacement vs. impact-energy/thickness ratio.

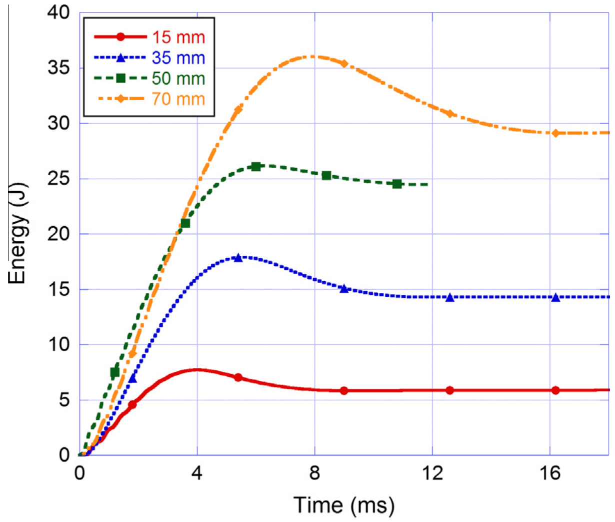

Fig. 8. Absorbed energy vs. contact time for a compression dynamic test at an impact-energy/thickness ratio around 500 J/m.

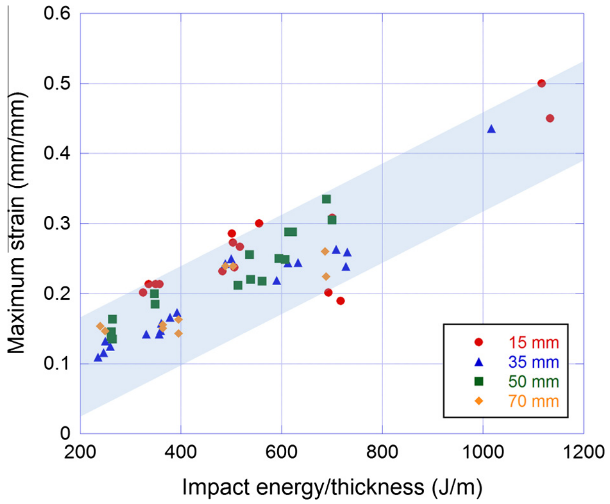

Fig. 6. Strain vs. impact-energy/thickness ratio.

The energy-history curves were completely different when drawn for the same impact-energy/thickness ratio (Fig. 8) because each specimen was tested with different impact energies. The absorbed energy was greater for the 70 mm thickness specimen, and less when the specimen thickness diminished. However, when the energy was divided by the thickness the variation of the energy/thickness ratio proved to be very similar to the behaviour noted in Fig. 7 for energy variation under the same impact energy. As can be seen in Fig. 8, the energy absorbed by the specimens is a high percentage of the impact energy. This behaviour was observed in all thicknesses and impact-energy/thickness ratios. Therefore, it is possible to affirm that the agglomerated cork is a material with a good energy absorption capacity [4]. The effect of thickness on the absorbed energy was analysed taking into account the influence of the impact-energy/thickness ratio. Fig. 9 shows the relationship between the absorbed energy and this ratio for the four specimen thicknesses studied. The absorbed energy is related with the displacement [13]. The displacement increases when the impact-energy/thickness ratio is increased (Fig. 5), thus also the absorbed energy increases (Fig. 9). A good correlation of data to a straight line was found, with R^2 being between 0.9933 and

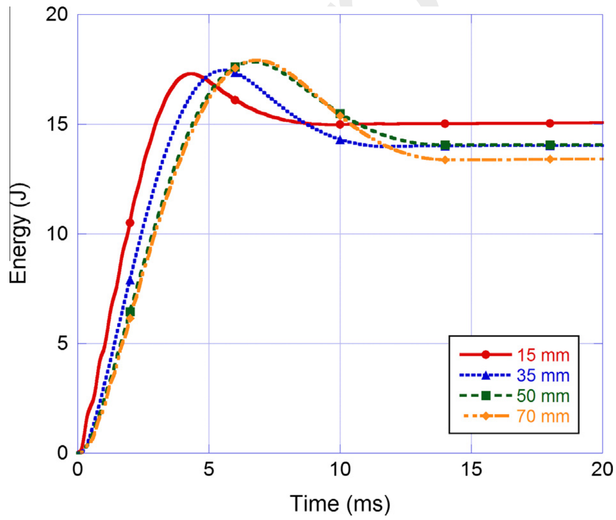

Fig. 7. Energy vs. contact time for dynamic crushing tests at an impact energy around 17 J.

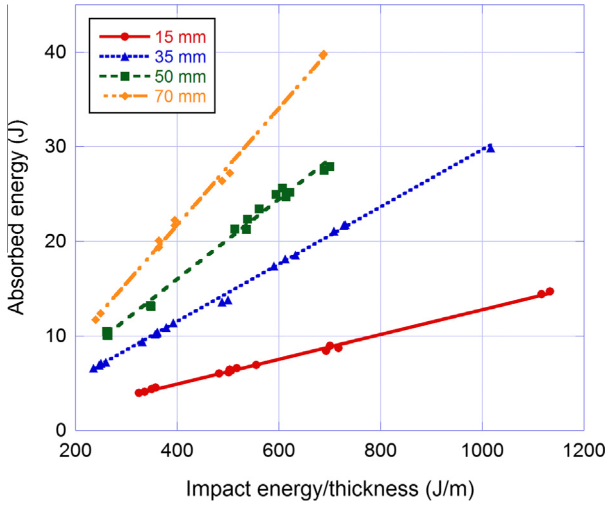

Fig. 9. Absorbed energy vs. impact-energy/thickness ratio.

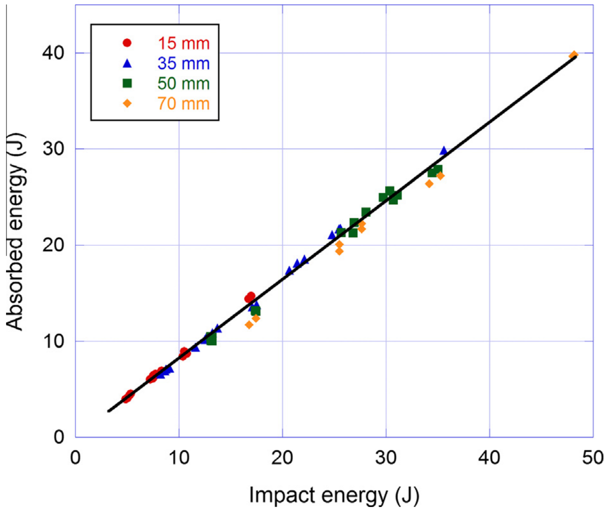

Fig. 10. Absorbed energy vs. impact energy.

0.9972. The slope of the fitting lines in Fig. 9 became steeper with greater specimen thickness. Therefore it is possible to assume a linear variation of absorbed energy with the ratio for each thickness within the range of impact energies analysed in this study.

In the Fig. 10 the relationship between the impact energy and the absorbed energy for all specimens show a good correlation with a straight line (R^2 equal to 0.9989). From this figure, it can be assumed that specimen thickness has no significant influence on the absorbed energy within the range of impact energies and thicknesses studied. This behaviour differed from that of polymeric foam [24]. These differences can be related to the dissimilar microstructure of foam and cork.

4. Conclusions

In this work, the dynamic crushing behaviour of agglomerated cork was studied experimentally. The influence of thickness on the energy-absorption capabilities of the cork was evaluated. The following conclusions were drawn:

- The maximum contact force, the maximum displacement, and the maximum strain exhibit a large dispersion, perhaps due to the natural origin of agglomerated cork and variation of properties between each specimen. Despite this dispersion, these variables incremented when the impact-energy/thickness ratio increased.
- An increment of the specimen thickness reduced the contact force for the same impact energy. Similar behaviour for the displacement and strain was not observed due to the dispersion of results.
- The relationship between the absorbed energy and the impact-energy/thickness ratio is linear for each specimen thickness studied.
- The energy-absorption capability of the agglomerated cork does not depend on the thickness of specimen in the range of energies analysed.

Acknowledgements

The authors are indebted to Amorim Cork Composites for providing the agglomerated cork used in the tests.

References

[1] Scarponi C, Pizzinelli CS, Sanchez-Saez S, Barbero E. Impact load behaviour of Resin Transfer Moulding (RTM) hemp fibre composite laminates. J Biobased Mater Bioenergy 2009;3(3):298–310.
[2] Scarponi C, Schiavoni E, Sanchez-Saez S, Barbero E, Sarasini F. Polypropylene/hemp fabric reinforced composites: manufacturing and mechanical behaviour. J Biobased Mater Bioenergy 2012;6(4):361–9.
[3] Hoto R, Furundarena G, Torres JP, Muñoz E, Andrés J, García JA. Flexural behavior and water absorption of asymmetrical sandwich composites from natural fibers and cork agglomerate core. Mater Lett 2014;127:48–52.
[4] Fernandes FAO, Pascoal RJS, Alves de Sousa RJ. Modelling impact response of agglomerated cork. Mater Des 2014;58:499–507.
[5] Mir A, Bezzazi B, Zitoune R, Collombet F. Study of mechanical and hygrothermal properties of agglomerated cork. Mechanika 2012;18(1):40–5.
[6] Mano JF. Creep-recovery behaviour of cork. Mater Lett 2007;61(11–12):2473–7.
[7] Gil L. Cork composite: a review. Materials 2009;2:776–89.
[8] Macías-García A, Díaz-Díez MA, Cuerda-Correa EM, Díaz-Parralejo A, Gómez-Serrano V. Use of cork agglomerates as acoustic absorbents. Mater Technol 2009;24(2):114–8.
[9] Anjos O, Pereira H, Rosa ME. Effect of quality, porosity and density on the compression properties of cork. Holz als Roh- und Werkstoff 2008;66(4):295–301.
[10] Anjos O, Pereira H, Rosa ME. Tensile properties of cork in the tangential direction: variation with quality, porosity, density and radial position in the cork plank. Mater Des 2010;4(31):2085–90.
[11] Anjos O, Pereira H, Rosa ME. Tensile properties of cork in axial stress and influence of porosity, density, quality and radial position in the plank. Eur J Wood Wood Prod 2011;69(1):85–91.
[12] Reis L, Silva A. Mechanical behaviour of sandwich structures using natural cork agglomerates as core materials. J Sandw Struct Mater 2009;11:487–500.
[13] Castro O, Silva JM, Devezas T, Silva A, Gil L. Cork agglomerates as an ideal core material in lightweight structures. Mater Des 2010;31(1):425–32.
[14] Moreira RAS, de Melo FJQ, Dias Rodrigues JF. Static and dynamic characterization of composition cork for sandwich beam cores. J Mater Sci 2010;45(12):3350–66.
[15] Gameiro CP, Cirne J. Dynamic axial crushing of short to long circular aluminium tubes with agglomerate cork filler. Int J Mech Sci 2007;49(9):1029–37.
[16] Alcântara I, Teixeira-Dias F, Paulino M. Cork composites for the absorption of impact energy. Compos Struct 2013;95:16–27.
[17] Coelho RM, Alves de Sousa RJ, Fernandes FAO, Teixeira-Dias F. New composite liners for energy absorption purposes. Mater Des 2013;43:384–92.
[18] Costas M, Díaz J, Romera LE, Hernández S, Tielas A. Static and dynamic axial crushing analysis of car frontal impact hybrid absorbers. Int J Impact Eng 2013;62:166–81.
[19] Tay YY, Lim CS, Lankarani HM. A finite element analysis of high-energy absorption cellular materials in enhancing passive safety of road vehicles in side-impact accidents. Int J Crashworthiness 2014;19(3):288–300.
[20] Anjos O, Rodrigues C, Morais J, Pereira H. Effect of density on the compression behaviour of cork. Mater Des 2014;53:1089–96.
[21] Sanchez-Saez S, Barbero E, Cirne J. Experimental study of agglomerated-cork-cored structures subjected to ballistic impacts. Mater Lett 2011;65:2152–4.
[22] Tomás-Pardo E. Desarrollo de una metodología para la medición de la velocidad en impactos de baja energía. Grade Thesis. University Carlos III of Madrid; 2009 [in Spanish].
[23] Garcia-Castillo SK. Análisis de laminados de materiales compuestos con precarga en su plano y sometidos a impacto, Ph.D. Thesis. University Carlos III of Madrid; 2007 [in Spanish].
[24] Di Landro L, Sala G, Olivieri D. Deformation mechanisms and energy absorption of polystyrene foams for protective helmets. Polym Testing 2002;21(2):217–28.
[25] Viot P, Beani F, Lataillade J-L. Polymeric foam behavior under dynamic compressive loading. J Mater Sci 2005;40:5829–37.
[26] Bouix R, Viot P, Lataillade J-L. Polypropylene foam behaviour under dynamic loadings: strain rate, density and microstructure effects. Int J Impact Eng 2009;36:329–42.
[27] Sanchez-Saez S, Barbero E, Navarro C. Compressive residual strength at low temperatures of composite laminates subjected to low-velocity impacts. Compos Struct 2008;85:226–32.