Strain Rate Effects of Polymeric Foam Cores under Compressive Loading

Rejab, M.R.M.
Tarmidi, N.U.A.
Zuki, N.M.
Noor, M.M.

ABSTRACT

Polymeric foams are widely used as core materials in various applications such as in cushioning, padding, insulating, structural use and buoyancy. This is because of its ability to provide high bending stiffness tied with lightweight in sandwich construction. The purpose of this paper is to investigate the strain rate effects to the polymeric foam cores under compression load. The case study included rigid polyurethane (PUR), low density polyethylene (LDPE) and polystyrene (PS) foam cores. In order to study the strain-rate dependence for these three different foams, compression tests based on the ASTM D 1621 were conducted over a range in strain rates of 0.0001 s^{-1} to 0.01 s^{-1} under the 50kN-Instron universal testing machine. From the compression data, the stress-strain curves were produced. The results from the tests show that when the strain rate is higher, the area under the plateau region increases and higher amount of energy can be absorbed. The results also shows that the collapse stresses of the foams increased linearly with the logarithm of the strain rate.

Keywords: *compression load, polymeric foam, strain rate effects*

Introduction

Polymeric foam materials have a cellular structure with a three-dimensional array of cells and they are being used increasingly in engineering applications (see Figure 1). The four major areas of application for cellular materials are thermal insulation, packaging, structural use and buoyancy. These applications of foams eventually caused them to be loaded with compression. However, their mechanical behaviours are complex due to their cellular structure (Gibson & Ashby, 1997).

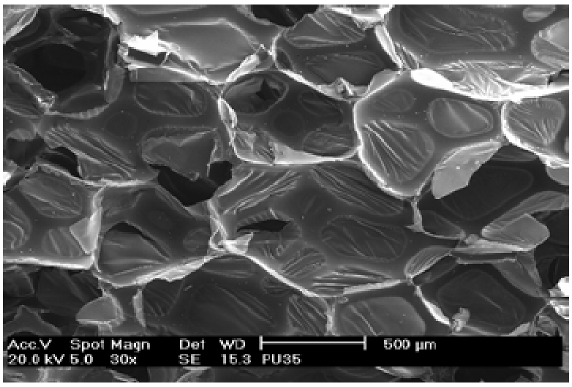

Figure 1: Three-dimensional Array of Cells of Polymeric Foam.

The cell structure of polymeric foams is a complex feature incorporating the polyhedral cell nature, cell strut shape and dimensions, cell window integrity and thickness, and cell size. Compressive strength of the foam can be increased by parallel alignment of the fibres and increasing cell size. The low strength and large compressive strain makes foams suitable for energy-absorbing application because the energy is absorbed as the cell walls bends plastically, buckle, or fracture depending on the stress that is limited by the long, flat, and almost horizontal plateau of the stress-strain curve. The plateau region however depends on the material and density of the foam. For the energy absorption purpose, with the right cell wall material and density, foams can be designed based on the requirements. More materials tests are required to determine their mechanical properties for structural design and numerical simulation purposes (Li et al., 2000). Due to the interest of polymeric foams, many researchers had done several studies to determine the mechanics, behaviours and properties of the foams [see (Triantafillou et al., 1989), (Alias and Mines, 1998), (Mines et al., 1997), (Avalle et al., 2000), (Song et al, 2003), (Saha et al., 2005)]. This paper is presenting the strain rate effects of polymeric foam cores under compressive loading. The focus is more on behaviour of foam cores under static compressive loading with three different foam cores e.g. rigid polyurethane (PUR), low density polyethylene (LDPE) and polystyrene (PS).

Material Preparation

The samples were prepared from slab stock foam into cubes with dimensions of 25mm x 25mm x 25mm as shown in Figure 2(a). The foam weight was determined by using electronic weighting scale (see Figure 2(b)). The density of foam, ρ was measured according to standard ASTM D1622-1998. The average apparent density of the PUR, LDPE and PS foam was 40.5 ± 0.5 kg/m^3, 30.5 ± 0.5 kg/m^3 and 18.5 ± 0.5 kg/m^3, respectively.

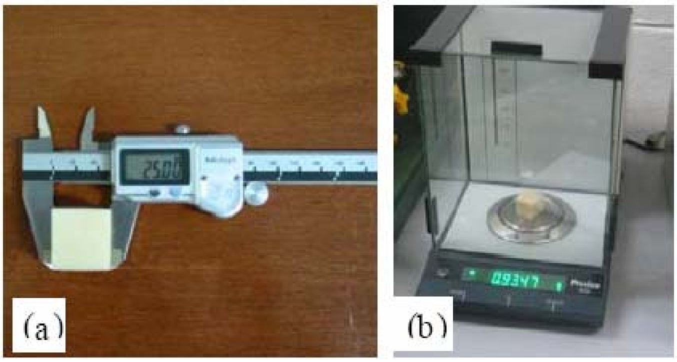

Figure 2: (a) Specimen Dimension, (b) Measuring Foam Weight.

Experimental Work

Compression test was conducted in an INSTRON Model 3369 testing machine according to standards ASTM D1621-1987. The specimens were 25mm thick, and other dimensions were same, 25mm by 25mm. As shown in Figure 3, the specimen was placed between the platens of the machine and was deformed at a quasi-static loading rate. The crosshead speed were varied into 5 different stages to obtain 5 different strain rates; 1mm/min, 5mm/min, 10mm/min, 15mm/min, and 20mm/min. The compression stress is calculated by using simple compression calculation;

$$\sigma_c = F/A$$

where: σ_c = core compression strength (MPa)
F = load (N)
A = cross-section area (mm^2)

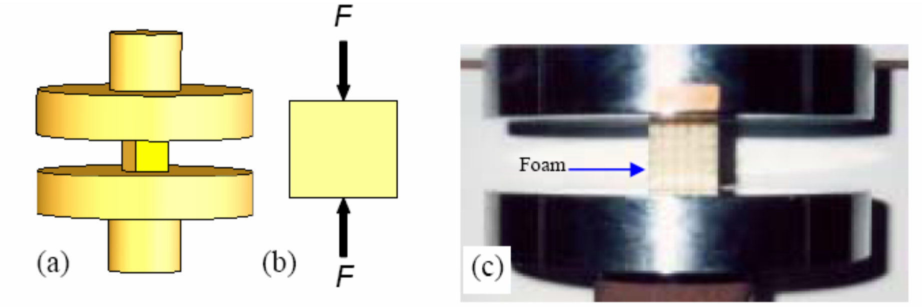

Figure 3: Compression Test (a) Setup, (b) Free-body Diagram of Compression Loading (c) Picture of Specimen Before Compression test.

Behaviour of Foam Cores

The compression process of foam has been described by Gibson and Ashby (1997), which has the general feature of localised progressive collapse. Typical engineering compression stress-strain curve tested at the three mutually perpendicular directions of the foam is shown in Figure 4 and it can be seen that the stress-strain curves is similar in these three directions. Stress-strain curve in other directions have not been measured because of this foam was assumed to be isotropic foam.

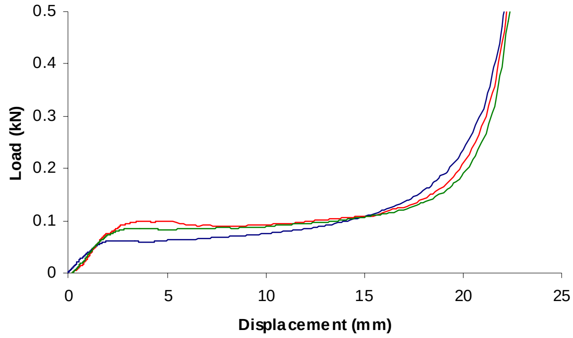

Figure 4: Shows the Mechanical Deformation in Compression Test. Compression in the PUR Foam gives Rise to the Three Phases of Response, Each Corresponding to Distinct Deformation Mechanisms.

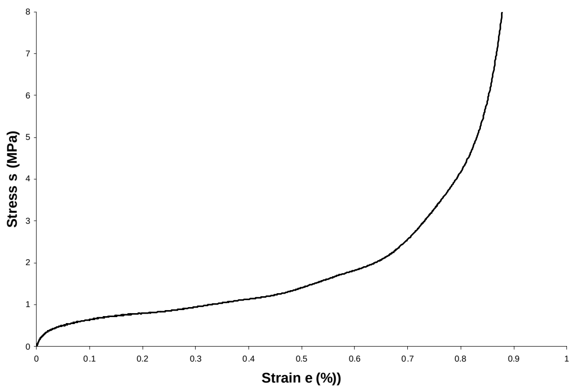

Figure 5: Typical Compression Stress-strain Curve.

The initial linear elasticity was controlled by elastic axial compression and bending of cell edges, stretching of cell faces and compression of gas within closed cells. Deformation during this phase was small, proportion and uniformly distributed throughout the specimen. Linear elasticity was limited to small strain, typically 15% or less. In the plastic plateau phase, cells collapse via buckling, plastic deformation or rupture of cell walls and edges. Deformation in this stage was not uniformly distributed and accounts for the major portion of the global response. Final densification was associated with completely collapsed cells being compacted against one another. Plastic collapse caused the cells to crumple in compressive direction and become thin. Deformation was uniformly distributed and the stress rises steeply as solid cell wall material was pressed together.

Results

Polystyrene (PS) Foam

From the stress strain curve as plotted in Figure 6, it can be seen that the linear elasticity region ends at ±4 % of strain. This is the point where the foam started to yield and then starts plateau region. The plateau region, as expected for the closed cell structure looks like a long, horizontal plateau, however it is not flat as it rises by strain due to the compression of air in the closed cells. By the end of the plateau region where the densification starts, the densification of the foam started to occur at ±65% of strain.

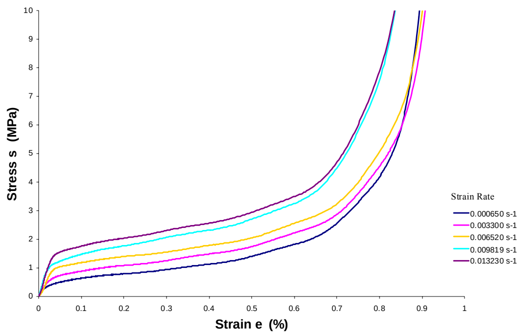

Figure 6: Stress-strain Curve for PS Foam with Increasing Strain Rates ($10^{-3.3}s^{-1}<\varepsilon<10^{-1.7}s^{-1}$).

The plateau region of the polystyrene foam shows that the bending moment of the cell wall rotation increased a little along with the long, horizontal plateau. When the collapse almost completed, this is where the foam started to fail, where the opposing cell wall started to contact with each other and crushed together, thus leading for the final densification region. For the tested polystyrene, it gives ±65% of densification strain and the curve then started to rise steeply.

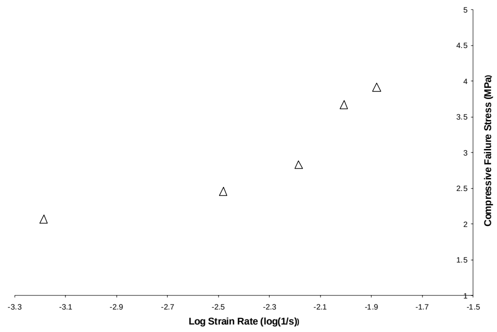

Figure 7: Compressive Failure Stress, σ_f versus Log Strain Rate (log(1/s)).

Based on the compressive failure stress obtained from the stress-strain curves, a graph of compressive failure stress, σ_f versus log strain rate (log(1/s)) was plotted in Figure 7 above and based on the graph, an equation as shown in equation (1) was produced to describe the strain rate dependence of failure stress at low strain rates,

$$\sigma_f = \sigma_{ry} + \mathrm{A}\log\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_r}\right),\ \text{for } 10^{-3.3}\ \mathrm{s^{-1}} < \dot{\varepsilon} < 10^{-1.7}\ \mathrm{s^{-1}} \qquad (1)$$

where $\dot{\varepsilon}_r = 10^{-3.19}\ \mathrm{s^{-1}}$ is the reference strain rate, $\sigma_{rf} = 2.07\ \mathrm{MPa}$ is the failure stress at $\dot{\varepsilon}_r$ and A is a constant determined from the experimental curve, where $\mathrm{A} = 0.76\ \mathrm{MPa}$.

Low Density Polyethylene (LDPE) Foam

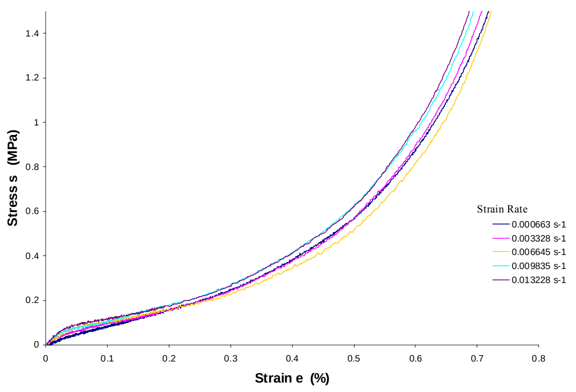

Figure 8: Stress-strain Curve for LDPE with Increasing Strain Rates ($10^{-3.3}\ \mathrm{s^{-1}} < \dot{\varepsilon} < 10^{-1.7}\ \mathrm{s^{-1}}$).

Polyethylene, elastomeric foams with closed-cell structure, recovered immediately. When the compression head platen released from the compressed surface, the flexible closed-cell PE returned to their original shape after compressed and can obviously be observed after the compression test finished. This is because of it is the nature of physical properties of the foam, that they have "memory" which caused them to return back to the original shape. The linear elasticity region of PE is not as same as closed-cell PS before even though both are closed-cell. The yield stress of the foam is determined by setting an offset to the graph by 2% of strain rate

(Figure 8).

The deformation then followed by the plateau region, the line increased by strain until the densification process of the foam started at ±19% of strain. From the stress-strain curve of LDPE foam, the compressive failure force, σ_f and the logarithm of strain rates (log (1/s)) can be calculated. The compressive failure force versus logarithm strain rates (Figure 9) was constructed and an equation that validates the relationship between the two parameters was produced. From equation (2) below;

$$\sigma_f = \sigma_{rf} + \mathrm{A}\log\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_r}\right), \text{for } 10^{-3.3}\ \mathrm{s}^{-1} < \dot{\varepsilon} < 10^{-1.7}\ \mathrm{s}^{-1} \qquad (2)$$

with $\dot{\varepsilon}_r = 10^{-3.18}\ \mathrm{s}^{-1}$ as the reference strain rate, $\sigma_{rf} = 0.15\ \mathrm{MPa}$ as the reference yield and the constant value of $\mathrm{A} = 0.007\ \mathrm{MPa}$ were derived from the graph.

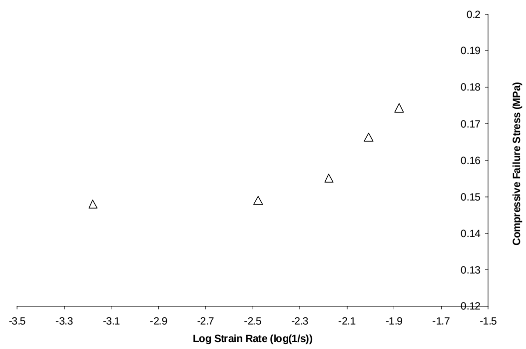

Figure 9: Compressive Failure Stress, σ_f versus Log Strain Rate (log(1/s)).

Rigid Polyurethane (PUR) Foam

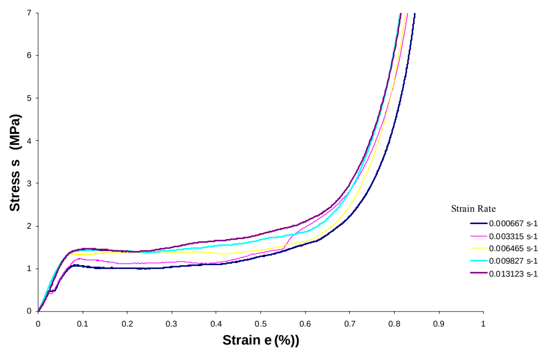

Figure 10: Stress-strain curve for PUR with increasing strain rates ($10^{-3.3}\ \mathrm{s}^{-1} < \dot{\varepsilon} < 10^{-1.7}\ \mathrm{s}^{-1}$).

Rigid polyurethane (PUR) foam was compressed as same as procedure of both LDPE and PS foams, with the same strain rate in range of $10^{-3.3}\ \mathrm{s}^{-1} < \dot{\varepsilon} < 10^{-1.7}\ \mathrm{s}^{-1}$. For open cell foam, the plateau region is almost flat, as the gas in side the cell were forced out during the compression, and compared to closed cell foam, the cell wall did not stretched, but bends. When the strain is at ±55%, the curve started to rise steeply and this where the densification occurred.

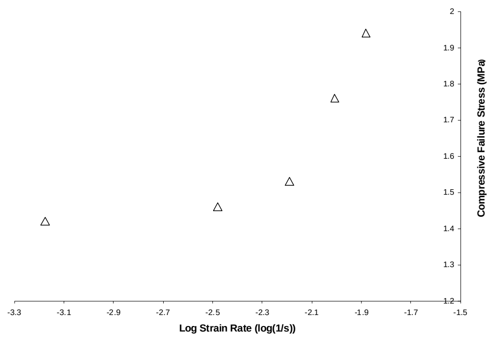

Figure 11: Compressive Failure Stress, σ_f versus Log Strain Rate (log(1/s)).

Based on the stress-strain curve (Figure 10), the strain rate increased as the crosshead speed increased, and the graph lies on top of each other. The yielding of the foam started to occur at ±8% to ±13% of strain as the strain rate increased, and the foam started densification at ±55% of strain.

From the equation (3),

$$\sigma_f = \sigma_{rf} + \mathrm{A}\log\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_r}\right), \text{for } 10^{-3.3}\ \mathrm{s}^{-1} < \dot{\varepsilon} < 10^{-1.7}\ \mathrm{s}^{-1} \qquad (3)$$

where, $\dot{\varepsilon}_r = 10^{-3.18}\ \mathrm{s}^{-1}$ is the reference strain rate with $\sigma_{rf} = 1.42\ \mathrm{MPa}$ as the reference yield at $\dot{\varepsilon}_r$ and $\mathrm{A} = 0.11\,\mathrm{MPa}$ is a constant derived from the experimental curve.

Discussion

According to the experimental results obtained from the compression tests, the structure of the cell wall, either closed or open gives different form of plateau region on the stress-strain curve. The stress-strain curve for PS foam, as shown in Figure 6 agrees with the graph produced from previous researchers, where the plateau region increasing with the strain. While for the open-cell PUR foam, the curve in Figure 10 shows that the plateau region is a long, flat and horizontal plateau. As for LDPE foam in Figure 8, the graph increased steeply, starting from the linear elasticity region until the densification region.

The initial yielding behavior of polymeric materials is sensitive to strain rate. By increasing the strain rate, the yield strength and the foam's strength can be increased, and thus increases the properties of the foams too. The yield stress for the foam compressed under 20mm/min, strain rate with $10^{-2}\ \mathrm{s}^{-1}$ gives higher yield. This is because, when the speed of the compression platen increased, the deformation of the foam will be faster, thus causing the foam to reach the yielding stress faster. However, the cell structure if the compressed foam under 20mm/min was not totally deformed compared to the cells compressed slowly under 1 mm/min or $10^{-3}\ \mathrm{s}^{-1}$.

The deformation of the foam depends on the behavior of the cell wall structure, whether the cells are open or closed-cell wall and the material that builds up the cell. This explains the behavior of the flexible closed-cell PE during and after the compression test. The plateau stress of LDPE foam, were determined by the elastic buckling of the cells, or else could be identified as a form of elastic deformation. Much of the external work done during the compression process was released when they were unloaded. The hysteresis, or damping condition of flexible foams however did not allow LDPE foam to be fully recovered, even after a certain length of time, as the structure were effected though it is not as much as the deformation in the closed-cell foam.

Conclusion

Polymeric foams are suitable for various applications due to their ability to undergo large compressive deformation, absorbs considerable amount of specific energy and mitigate shock loads. However, the amount of stress that can be endured by the foams depends on the plateau region of the stress-strain curve. While plateau region depends on the cell structure to determine the slope, either it is an increasing slope with strain or long-flat horizontal plateau.

Strain rate is important in determining the mechanical behavior of the foam. The amount of energy that can be absorbs depends on strain rate too. When the strain rate is higher, the area under the plateau region will increase, thus gives higher amount of energy can be absorbed. Therefore, from the tests conducted, it can be concluded that strain rate was an important factor in determining the strength to absorb energy and the yield strength of the foam, which increases with strain rate.

When the compression rate was low, for an example 1mm/min that gives 10^{-3} s^{-1} of strain rate, the time for the force to be distributed to the cell edges will be longer, causing the cell to collapse slowly, and thus the yield stress is lower, and the plateau region longer. The opposite behavior occurred when the time to compress the foam is reduced by increasing the compression head speed. The cell will not be totally deformed, although they were compressed under the same load. Therefore, yielding point occurred at higher stress, and the plateau region will be shorter

Acknowledgment

The authors would like to express their thanks to the Universiti Malaysia Pahang for funding this project.

References

Alias A. and Mines, R.A.W. (1998). Experimental Results and Techniques on the Crush Behaviour of Structural Foam. *The 3rd Int. Symposium on Impact Eng., Singapore*. 379-284.

Avalle, M., Belingardi, G. and Montanini, R. (2000). Characterization of polymeric structural foams under compressive impact loading by means of energy-absorption diagram. *International Journal of Impact Engineering*, 25, 455-472.

Bo Song, Chen, W.W., and Kang, J.H. (2003). Strain-rate effects on elastic and early cell-collapse responses of a polystyrene foam, *International Journal of Impact Engineering*, 31, 509–521.

Gibson, L.J and Ashby, M.F. (1997). *Cellular Solids Structures and Properties,* Second Edition, United Kingdom: University Press, Cambridge.

Li, Q.M., Mines, R.A.W and Birch, R.S. (2000). The Crush Behaviour of Rohacell-51WF Structural Foam. *Int. J. of Solids & Structures,* 37, 6321-6341.

Mines, R.A.W., Li, Q.M., Alias, A., Birch, R.S., and Close, J.A. (1998). On the Measurement of the Crush Behaviour of Structural Foams. *Proceeding of the 11th International Conference on Experimental Mechanics, Oxford*.

Saha, M.C, Mahfuz, H., and Chakravarty U.K. (2005). Effects of density, microstructure, and strain rate on compression behavior of polymeric foams. *Materials Science and Engineering: A*, 406, 328-336

Triantafillou, T.C., Zhang, J., Shercliff , T.L., Gibson, J.L. and Ashby, M.F. (1989). Failure Surface for Cellular Materials under Multiaxial Loading-II Comparison of Model with Experimental. *Int. J.of Mech. Sci.,* 31**,** 665-678.

REJAB, M.R.M., TARMIDI, N.U.A., ZUKI.N.M. & NOOR, M.M., Faculty of Mechanical Engineering, Universiti Malaysia Pahang, Locked Bag 12, 25000 Kuantan, Pahang. ruzaimi@ump.edu.my