Compressive Response and Energy Absorption of Foam EPDM

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ABSTRACT: Ethylene–propylene–diene terpolymer foam was prepared by two different processing routes. The microstructure and mechanical properties of the foams with wide relative density ranging from 0.11 to 0.62 have been studied via scanning electron microscopy and mechanical testing, respectively. Scanning electron microscopy shows that the foam with lower relative density has a unique bimodal cell size structure, which the larger cells inlay among the smaller cells, while the foam articles with higher relative density have thicker cell walls with few small cells. The compressive stress–strain curves show that the foam articles with lower relative density have three regimes: linear elastic, a wide slightly rising plateau, and densification, while the foam articles with higher relative density have only two regimes: the longer linear elastic and densification. The relative modulus increases with the increase in the relative density. The contribution of the gas trapped in the cell to the modulus could be neglected. The energy absorbed per unit volume is relationship with the permitted stress and the relative density. The efficiency and the ideality parameter were evaluated from the compressive stress–strain plots. The parameters were plotted against stress to obtain maximum efficiency and the maximum ideality region, which can be used for optimizing the choice for practical applications in cushioning and packaging. © 2007 Wiley Periodicals, Inc. J Appl Polym Sci 105: 3462–3469, 2007

Key words: EPDM; compression; foam; energy absorption

INTRODUCTION

Polymeric foam structures came into general practical use during the 1940s and 1950s. Now foam materials are increasingly being used in engineering system on account of their unique structural properties. These properties include physical comfort, effective packaging, gentle energy absorption, good insulation, and cushioning properties. These advantages lead to many applications, such as thermal insulation, buoyancy, packaging, and gaskets.

The applications generally involve large material deformations, which is the result of the foam material's microstructure. A complex three-dimensional network of struts and membranes undergo large deformations and contact during deformation. The general compressive stress–stain curves of low relative density foams include three regimes.[1,2] First is an elastic response at small deformations, during which the network deforms fairly uniformly. Second is an elastic collapse stage where localized bending occurs at weak points in the network. As the structural configuration evolves, new weak points are created and high degrees of bending propagate throughout the microstructure. It is the large deformation region that is the most characteristic of foams and results in the stress plateau where larger displacements occur at almost constant force. Finally, there is a densification phase when the network is collapsed onto itself and contact between network elements, which results in dramatic stiffening of the material. Although actual cell microstructure is very complicated, these regimes of deformation have been studied extensively and significant understanding has been obtained using idealized models.[3–9] Currently, the quite popular theoretical model used to predict the compression properties of low density foams was put forth by Gibson and Ashby,[2] which shows that in idealized cubic cell model the mechanical properties are closely relative to the foam relative densities and material properties, which is further proved by many experimental results.[1,10,11] For high density foams, Moore et al. proposed an empirical expression for the modulus of polypropylene foams.[5] In compression process, a particularly unusual aspect of foams is the large capacity to absorb energy, which stems from the large deformation of

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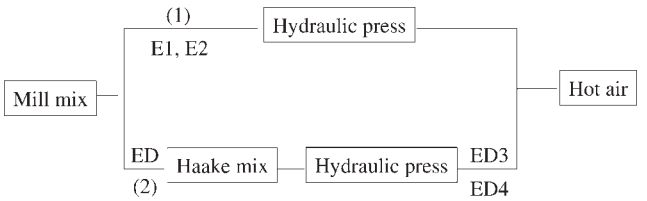

Figure 1 Schematic illustration of the fabrication process for EPDM foam.

cell walls and edge. The energy absorption characteristics of foams have been evaluated by efficiency and ideality parameters.[12–15]

It is well known that ethylene–propylene–diene terpolymer (EPDM) has chemical stability, good ageing resistance, and high resistance to breakdown during mechanical operations. Now EPDM finds increasing acceptance for producing cellular sections.[16–18] Because higher-surface-area carbon black may lead to some problem[19] during blowing process for the stiffness of the rubber compound generated, in general, the conventional EPDM foam formulation contains nonreinforcing filler, such as whiting or talc etc., used as nucleating agent, and lower-surface-area carbon black, such as N550, N650, N722 etc., is used as reinforcing filler. However, the filler with lower surface area gives a lower reinforcing effect, which would lead to resultant foam with lower mechanical properties. Thus, it is important to improve the properties of the matrix to achieve the foam mechanical properties.

In this article, we will show a simple rubber compound formulation to prepare the EPDM foam in a circular hot air oven. We adopt the higher-surface-area carbon black N330 as reinforcing filler, which is hardly ever used for EPDM foam for too much reinforcing effect, and without oil and nucleation. In general, it is difficult to prepare optimum foam structure for too much reinforcing effect and matrix modulus. And we also study the compression properties of EPDM foams with wide relative density range between 0.11 and 0.62, and focused on the relationship between the energy absorption capacity and the foam relative density. We then evaluated the efficiency, ideality, and energy absorption diagram in optimizing the choice of foam for practical applications in cushioning and packaging.

EXPERIMENTAL

Materials

EPDM (Keltan 4703, ENB 9 wt %) manufactured by DSM Elastomers (Sittard, The Netherlands) was used; carbon black (N330) supplied by Shanghai Cabot Chemical Co., Ltd. (Shanghai, China) was used as filler; and azodicarbonamide was produced by Shanghai Xiangyang Chemical, China. All the other additives were rubber industrial grade products.

Compounding and sample preparation

The basic ingredients of EPDM foams in this study are identical each other, except different blowing agent content, which disappear for decomposition in the process. The preparation process of EPDM sponge is shown in Figure 1. There are two different process paths:

1. *The preparation of foam E1 and E2:* First, EPDM was compounded with the ingredients on a two-roll mill according to the formulations listed in Table I. Then the compound was placed in a 100 × 100 × 5 mm^3 mold, it was loaded in a hydraulic press at room temperature under 10 MPa in 10 min, the approved product was stored at room temperature for 24 h, and finally the approved product was placed in a circulating hot air oven for foaming and vulcanizing at 195°C for 10 min, respectively.
2. *The preparation of foam ED3 and ED4:* The processing routes are similar to the above except that of partially precured process, which lies between the mix and hydraulic press. The partially procured process was performed in a HAAKE Rheometer at 80 rpm at 80°C for 10 and 15 min, respectively.

Density measurements

Density (ρ*) of foam article was calculated from the mass and volume of specimens with surface skins, according to ISO 845-1988. The relative density (ρ_R) of the foam materials is the density of the specimens normalized by the density of solid EPDM ($\rho_s = 1.04$ g/cm^3).

Scanning electron microscopy observations

The cellular morphologies of the foam samples were observed by scanning electron microscopy (SEM, Model *S*-2150, HITACHI). Samples were razor-cut

TABLE I
Rubber Compound Formulations for Foaming Process

Materials	E1	E2	ED
EPDM (Keltan 4703)	100	100	100
Stearic acid	2	2	2
Zinc oxide	4	4	4
Carbon black (N330)	20	20	20
Calcium oxide	3	3	3
Diphenylguanidine	2	2	2
Sulfur	1.5	1.5	1.5
Azodicarbonamide	10	8	6

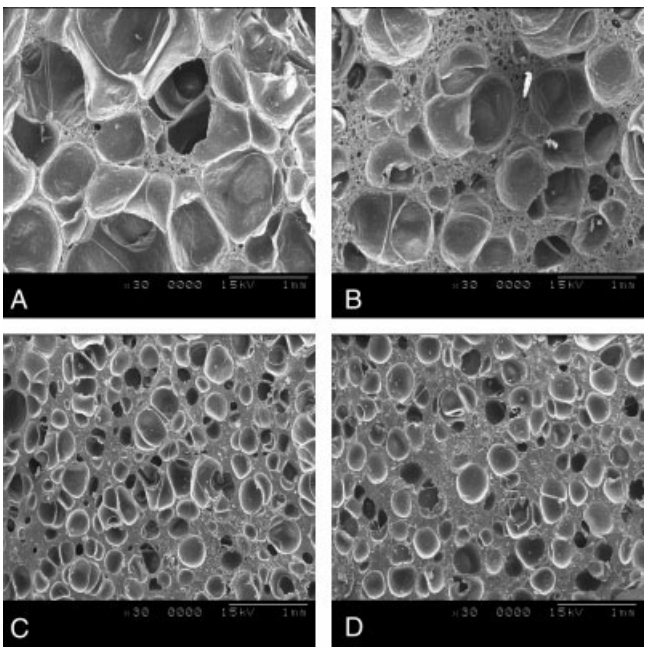

Figure 2 SEM photomicrograph of razor cut surfaces of EPDM. (A) E1 ($\rho_R = 0.11$); (B) E2 ($\rho_R = 0.20$); (C) ED3 ($\rho_R = 0.51$); (D) ED4 ($\rho_R = 0.62$).

and the razor-cut surface was sputter-coated with gold before observation.

Mechanical properties

The uniaxial compression tests were carried out on cylindrical specimens of 50 mm in diameter and 15–25 mm in height on an Instron 4465 electromechanical tester equipped with 30 KN load cell according to ISO 3386 standard; the sample was placed between two parallel steel platens; and compression tests were performed by deforming the specimen to permitted stress (3.5 MPa) at a crosshead speed of 5 mm/min.

RESULTS AND DISCUSSION

Cell morphology

Figure 2 shows SEM micrograph of the EPDM foam, and it clearly shows two different kinds of images of the cellular structure. Foam E1 and E2 show a unique bimodal cell size structure, and there are a few open cells in the foams with the larger cells inlaying among the many smaller cells. As the relative density of foam EPDM is increased, the thickness of the larger cell edges and faces become thicker and the cell size of the lager cell is decreased, while the cell sizes of smaller cell lying between the larger cell edges and faces are roughly the same, regardless of their relative density. For foam ED3 and ED4, it is apparent that the foam articles have quite a few open cells and thicker cell walls with few small cells. With the increase in relative density, the thickness of the cell edges and faces is increased, while the cell sizes are roughly the same regardless of their relative density.

Compression behavior

Figure 3 shows compression stress–strain curves from EPDM foam samples with different relative density. The compressive stress–strain curve of foam E1 and E2 is typical curve of elastomeric foams, showing linear elasticity at low stresses, and the corresponding yield strain is about 0.03. Followed by a wide collapse plateau, which leads to densification where stress rises steeply, the value of the densification strain of foam E1 and E2 is 0.84 and 0.77, respectively. However, for the foam ED3 and ED4, the compressive stress–strain curve shows only two regions: the comparatively longer linear elastic region, then leads to densification where stress rises steeply; the value of the densification strain of foam ED3 and ED4 is 0.61 and 0.45, respectively. The difference of the compression stress–strain curves might be due to different foam density. According to Gibson–Ashby theory,[2] there is a transition at a normalized density of about 0.3 between a cellular structure and one better considered as a filled composite consisting of a matrix and isolated voids, which would lead to compressive behavior transition.

Linear elasticity region

According to Gibson–Ashby theory,[2] the linear elasticity is controlled by three different strains: bending of cell edges, compression of gas trapped into the

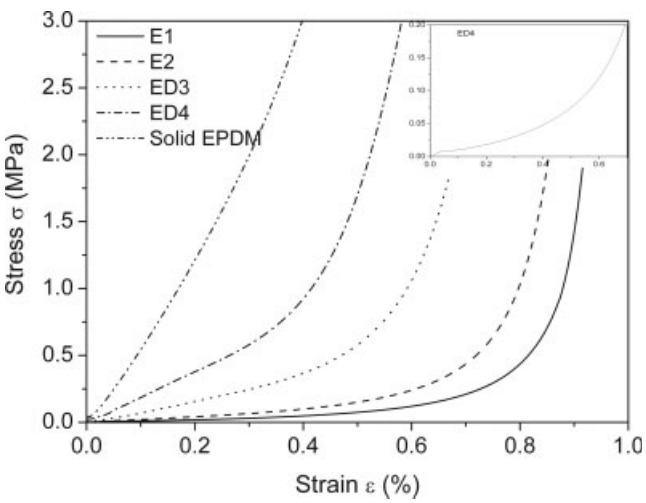

Figure 3 Uniaxial compressive behaviour of EPDM foam samples with varied relative density.

cells, and stretching of cell walls. Young's modulus E^* is the initial slope of the stress–strain curve and may be predicated by the following equation in the sum of three contributions.

$$\frac{E^*}{E_s} = \frac{E_c^*}{E_s} + \frac{E_f^*}{E_s} + \frac{E_g^*}{E_s} = \phi^2 \left(\frac{\rho^*}{\rho_s}\right)^2 + (1+\phi)\frac{\rho^*}{\rho_s} + \frac{P_0(1-2\nu^*)}{E_s(1-\rho^*/\rho_s)} \quad (1)$$

where φ is the volume fraction of the solid contained in the cell edges, E_s and E^* are Young's modulus of the solid material and the foam material, respectively, and the value of E_s is 6.04 MPa, which is tested in experiment. E_c^* is the contribution of bending of cell edges to modulus, E_g^* is the contribution of gas compression to modulus, E_f^* is the contribution of stretching of the wall membranes, $\frac{\rho^*}{\rho_s}$ is the relative density of foam articles, ν^* is the Poisson's ratio, which is usually assumed 0.33. P_0 is the initial pressure of the cell fluid in the closed cell. In our case, the fluid is gas, when the initial P_0 is the atmospheric pressure (0.1 MPa), the contribution is small, and can be neglected. Then eq. (1) is simplified as

$$\frac{E^*}{E_s} = \frac{E_c^*}{E_s} + \frac{E_f^*}{E_s} = \phi^2 \left(\frac{\rho^*}{\rho_s}\right)^2 + (1+\phi)\frac{\rho^*}{\rho_s} \quad (2)$$

This is famous Gibson–Ashby model for describing close-cell foam materials.

If $\varphi = 0$, which indicates the foam material without cell edges, then eq. (2) is simplified as

$$\frac{E^*}{E_s} = \frac{E_f^*}{E_s} = \frac{\rho^*}{\rho_s} \quad (3)$$

This might be taken as the simple rule of mixtures (Simple Blend Mode),[20] which based on the assumption the gas trapped in the cells is supposed as a kind of filler with zero modulus.

If $\varphi = 1$, which indicates the open foam material without cell faces, then eq. (2) is simplified as

$$\frac{E^*}{E_s} = \frac{E_c^*}{E_s} = \left(\frac{\rho^*}{\rho_s}\right)^2 \quad (4)$$

This is square-relation model, which is quite popular to predict the compressive modulus of open-cell foams put forth by Gibson–Ashby.[2]

Figure 4 summarizes the measured elastic modulus E^* normalized by those of the solid EPDM compound, and plotted against relative density. It can be found that the relative modulus increase with the

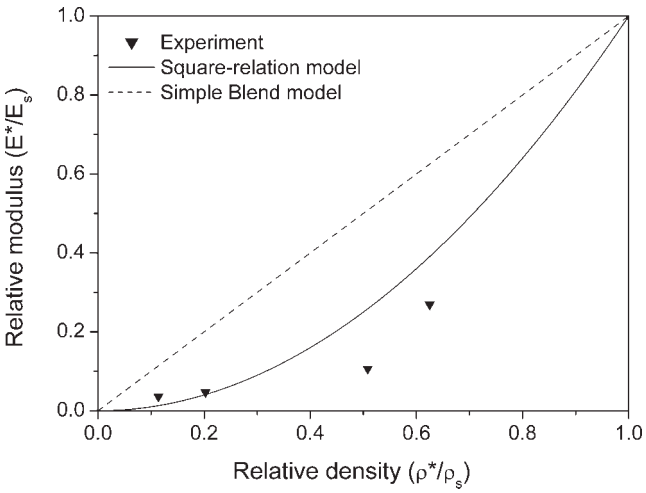

Figure 4 Comparison between theoretical and experimental data for compressive modulus of EPDM foam.

increase in relative density, as observed in all cellular solids. The value of relative modulus of foam E1 and E2 is 0.035 and 0.047, respectively, and the value locates between the eqs. (3) and (4), which indicates that eq. (2), Gibson–Ashby model, could describe the compressive behavior of foam E1 and E2. While the value of relative modulus of foam ED3 and ED4 is 0.106 and 0.269, respectively, and the value is below the value predicted by two equations, which indicates a large difference between the calculated relative modulus and the measured one. The difference is considered partially due to the problems in the foam processing, which lead to the cell edges and faces imperfect. While in Gibson–Ashby's model, cell edges and faces are considered as perfect solid materials from which the porous materials are made. Hence, the modulus (E_s) in eq. (2) should be the modulus of the porous cell edge and face rather than that of the solid materials. It is probably more important to realize that Gibson–Ashby's model is generally good for foam materials of relatively high porosity, typically above 70%. For higher relative density foam materials, it becomes questionable whether the solid part can be treated as beams or plates. This might be one of the major reasons for the large discrepancy between the model and the test results. Thus, it is a grand challenge to develop an understanding of the correspondence between characteristics of the microstructure and bulk response, which requires further study.

The contribution of gas trapped in the cells

The compressive stress–strain curves of foam E1 and E2 do not have a horizontal plateau, but exhibit a rising, postbuckling slope, which result from both compression of the gas trapped in the cells and

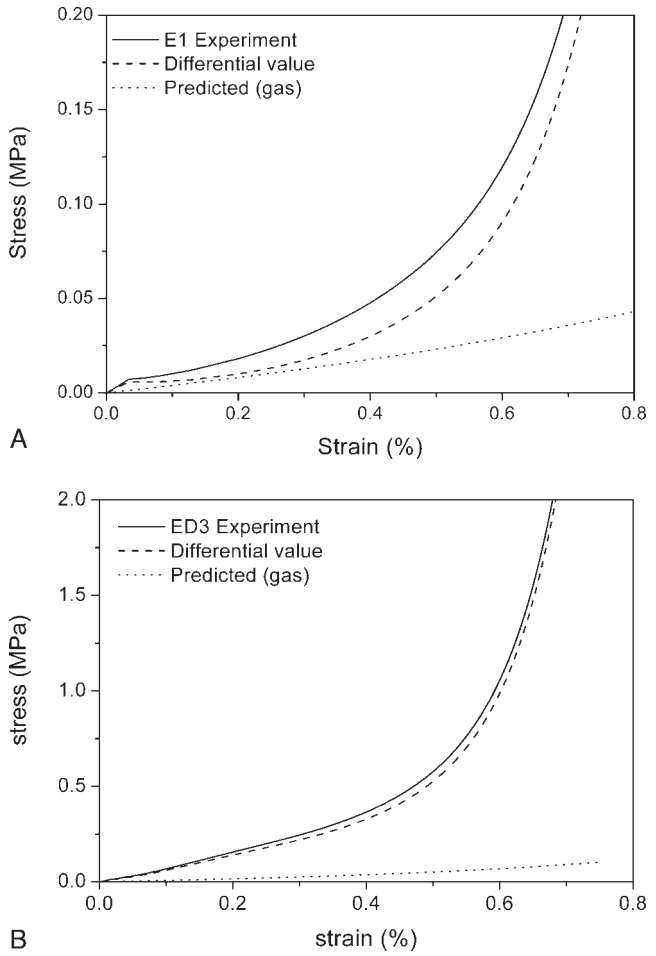

Figure 5 Compressive load deformation curve and the estimated contribution of trapped gas to the stress are indicated: (A) E1; (B) ED3.

membrance stresses. In theory, the contribution of gas to the stress might be calculated according to the formulation[2]

$$P_g = \frac{P_0\varepsilon(1-2\nu^*)}{1-\varepsilon(1-2\nu^*)-\rho^*/\rho_s} \quad (5)$$

where P_g is the gas pressure in the strain of ε, P_0 is the initial value of gas pressure (usually atmospheric pressure), and ε is the strain.

Figure 5 shows the compressive stress–strain experiment curves, the contribution curves of gas to the stress in theory and the differential values between the experiment and the theory. It clearly shows that the contribution of gas trapped in the cell to the stress increase with the strain increasing. The curve of differential values is similar to the curve of experiment in linear elasticity region, which indicates the contribution of gas to the elastic modulus of foam articles is negligible. The simplified eq. (2) is reasonable.

The densification phase

At large compressive strains, when the cells are completely collapsed, the opposing cell walls are crushed together and the constituent material is compressed as well. As a consequence, the stress–strain curve rises steeply and its slope tends to E_s, Thus, the transition to densification occurs at a strain (ε_D) where most of porosity has been squeezed out and solid behavior becomes dominant. The empirical relation[2] between densification strain and relative density is

$$\varepsilon_D = 1 - 1.4\frac{\rho^*}{\rho_s} \quad (6)$$

Figure 6 shows the relationship between ε_D and the relative density of foam. It clearly shows that the densification strain (ε_D) of foam E1 and E2 could be predicted by eq. (6), while the densification strain (ε_D) of foam ED3 and ED4 deviate from the predicted value by eq. (6), which shows that two kinds of foam materials have different compression deformation mechanism.

Energy absorption characteristics

During loading, the work acting on the sample is converted to potential energy or heat energy. The work per unit volume in deforming the foam at strain ε is the area under the stress–strain curve, which is called the energy absorption capacity (W), which is a function of stress and strain. A particularly unusual aspect of the mechanical behavior of foam is the large deforming capacity, which leads to a large capacity to absorb energy during compression loading.

Figure 7 shows the absorb energy during compression loading as a function of strain of samples with

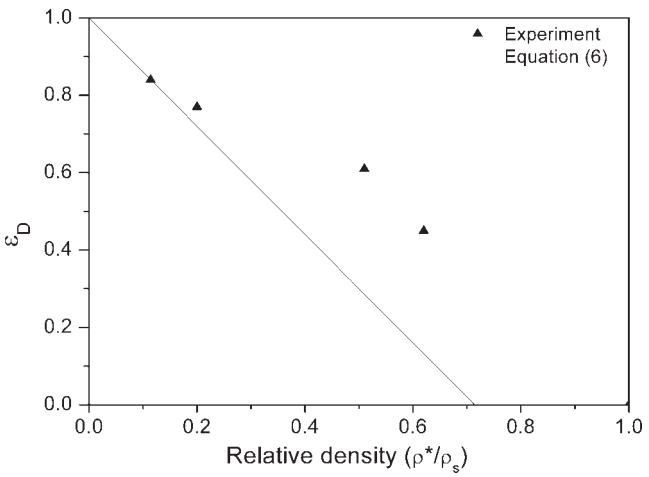

Figure 6 The effect of relative density on the densification strain.

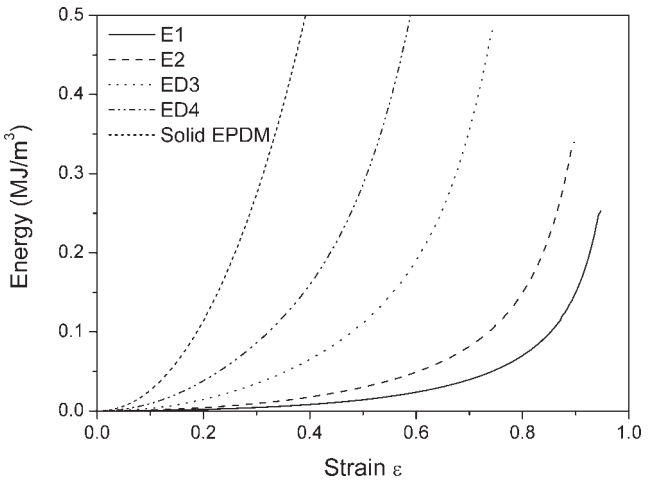

Figure 7 The effect of the strain on the specific energy dissipated.

varied relative densities. It can be observed that the absorption energy increases with the relative density in the same strain. However, the higher absorption energy is at the expense of higher loads transferred according to the Figure 8. In fact, the function of foam energy absorption is to prevent an applied force on an object from exceeding a permitted stress limit. Therefore, in practical applications, the energy absorption capacity is limited by the maximum permitted stress.

Figure 8 shows the energy absorption as a function of permitted compression stress of samples with varied relative densities. It can be observed that the relationship between the specific energy absorption and the relative density of foams is complicate. For instance, for a given permitted compression stress 0.1 MPa, the foam with relative density of 0.11 absorb energy of 0.02 MJ per cubic meter, while the foam with relative density of 0.51 absorb energy of only 0.006 MJ per cubic meter. In lower permitted stress, the higher energy absorption of lower relative density foams stems from the larger deformation, the bending and buckling of the cell walls and edges. For a given permitted compression stress 1 MPa, the foam with relative density of 0.11 absorb energy of 0.12 MJ per cubic meter, while the foam with relative density of 0.51 could absorb energy of more than 0.18 MJ per cubic meter. In higher permitted stress, the higher energy absorption of higher relative density foams stem from the higher modulus and larger deformation, while the lower density foams step into densification phase in higher permitted stress, which has little strain. Thus, the energy absorption capabilities are closely relationship with the relative density of foam article and the permitted stress, and the effect of foam density on the energy absorption capabilities is far more significant at the low stress of 0.1 MPa than at the high stress of 1 MPa. Once the maximum permitted stress is designed, the optimum energy absorption capability is accordance with the relative density of foam articles.

To evaluate and compare the performance and suitability of the energy absorption of different foam, Miltz et al.[12,13] define two parameters that are called the efficiency of energy absorption or efficiency (E) and the ideality parameter (I). The efficiency is defined as the ratio between the energy absorbed by an EPDM foam compressed to a maximum strain (ε_m) and that absorbed by an ideal EPDM foam that transmits the same maximum stress (σ_m) to the product when fully compressed.[12–15] Thus,

$$E = \frac{Ah\int_0^{\varepsilon_m}\sigma d\varepsilon}{Ah\sigma_m} = \frac{\int_0^{\varepsilon_m}\sigma d\varepsilon}{\sigma_m} \tag{7}$$

where h is the thickness of EPDM foam and A is the contact area. The ideality parameter (I) is defined as the ratio between the energy absorbed by an actual and an ideal cushioning material compressed to the same strain,[12–15] namely,

$$I = \frac{Ah\int_0^{\varepsilon_m}\sigma d\varepsilon}{Ah\sigma_m\varepsilon_m} = \frac{\int_0^{\varepsilon_m}\sigma d\varepsilon}{\sigma_m\varepsilon_m} \tag{8}$$

Thus, the efficiency (E) and ideality parameter (I) could be calculated from the stress–strain curves in Figure 3 using a computer program. Figure 9 shows the efficiency of energy absorption (E) as a function of stress of samples with varied relative densities. It can be observed that the efficiency goes through a maximum value but the maximum value is attained at a different stress for different foam. With decreasing relative density, the maximum value appears at

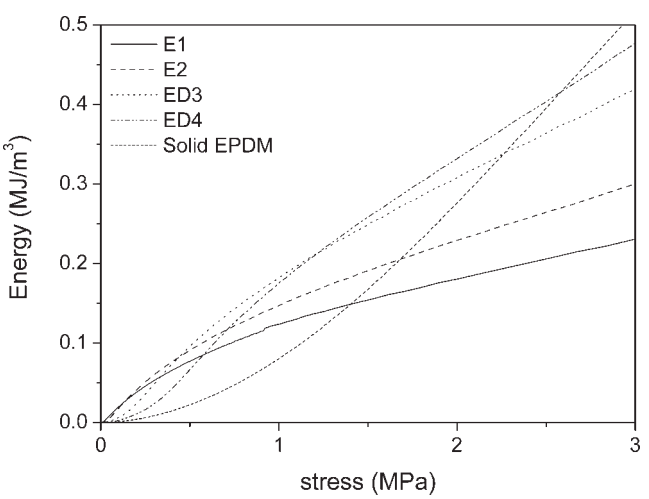

Figure 8 The effect of the stress on the specific energy dissipated.

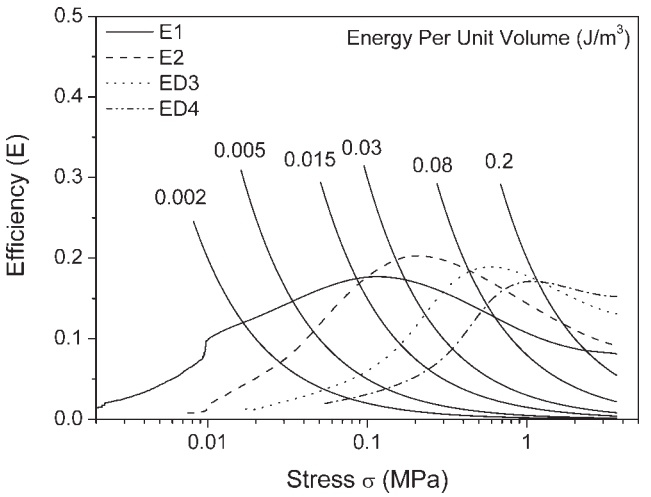

Figure 9 Efficiency of energy absorption of EPDM foams calculated from stress–strain curves.

lower stress, and the apex of efficiency curves becomes flat and the range of peak becomes wider. From eq. (7), it is evident that the product $E\sigma_m$ is equal to the energy per unit volume that is absorbed by EPDM foam when compressed to the strain ε_m and this product is a constant for a specific absorbed energy level. Thus, contours of constant energy levels can be superimposed in Figure 9. According to the contours, it is evident that different foam can absorb different amount of energy at its maximum value ($E_{\max}$).

Figure 10 shows the ideality of studied foams as a function of stress. It is obvious that the ideality curve goes through a maximum value. In comparison with the efficiency curve, the maximum value of the ideality is reached at a lower stress. This might be due to different deformation stage. The maximum value of the efficiency appears when the stress–strain curve start rising steeply, that is, where the densification phase takes place and the network of foam is collapsed onto itself and contact between network elements. Thus, the stress that the maximum value of the efficiency is corresponding with is the criterion of choosing the maximum load for EPDM foam in a cushioning application. However, ideality parameter shows a maximum value in the region of elastic collapse stage, where the bending, stretching, and compression of enclosed gas occurs. Thus, the maximum value of ideality is used as a foundation of choosing the optimal EPDM foam for improving the work efficiency of actual packaged item in energy absorption.

Energy absorption diagram

Maiti et al.[21] offer an energy-absorption diagram approach, which applies empiricism combined with physical modeling, for optimizing the choice of foam, which is proved having attractive generality.[14,15] A plot of the value of W versus σ, normalizing both by the modulus of EPDM solid ($E_s = 6.04$ MPa), is presented in Figure 11. The optimal foam for a given package is the one that absorbs the most energy up to the maximum permitted stress (σ_p). Each density of EPDM foam has a σ_p for which it is the best choice given by the shoulder on the energy curve, because, here, the curve for the foam lies above that of the other, the envelope of which describes a relationship between W and σ_p for the optimum density of EPDM foam. The envelope divides the diagram into an accessible region (below the line) and an inaccessible region (above the line). The equation of the envelope line for EPDM foam is approximately given by

$$\frac{W}{E_s} = 0.179\left(\frac{\sigma}{E_s}\right)^{0.99} \tag{9}$$

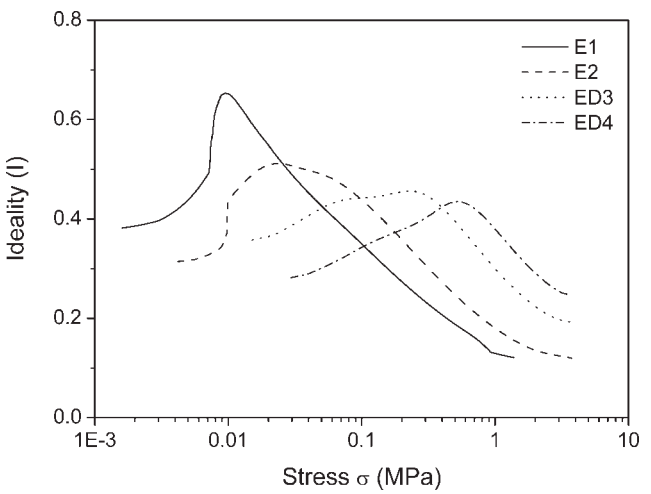

Figure 10 Ideality I of EPDM foams calculated from stress–strain curves.

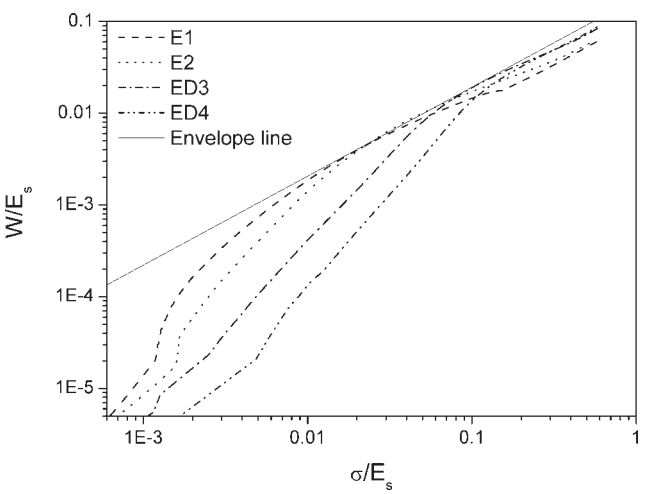

Figure 11 Energy absorption diagrams of EPDM foams calculated from stress–strain curves.

CONCLUSIONS

In this work, EPDM foam, including carbon black N330 as reinforcing filler, was prepared by two different processing routes. The microstructure and mechanical properties of the foams with wide relative density range from 0.11 to 0.62 have been studied via SEM and mechanical testing, respectively.

SEM shows that the foam E1 and E2 have a unique bimodal cell size structure, which the larger cells inlay among the smaller cells, while the foam ED3 and ED4 have thicker cell walls with few small cells. The compressive stress–strain curves show E1 and E2 have three regimes: linear elastic, a wide slightly rising plateau, and densification, while ED3 and ED4 have only two regimes: the longer linear elastic and densifications. The relative modulus of foam articles increase with the relative density increasing. In lower permitted stress, the higher energy absorption of lower relative density foams stems from the larger deformation, while in higher permitted stress, the higher energy absorption of higher relative density foams stems from the higher modulus and larger deformation. In comparison with the efficiency curve, the maximum value of the ideality is reached at a lower stress, which might be due to different deformation stage. From the energy-absorption diagram, there is an optimum foam density for a given packaging or energy absorbing application.

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