Dynamic Compression Characteristics of Flexible Foams. II. Density Variation

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Synopsis

In Part I, a simple mathematical model was proposed, based on dimensional similarity parameters, to describe the characteristics of flexible plastic foams under impact conditions. The model assumes that the foam is a rate-dependent material. In the present part we extended the similarity model, by including the density of the foam parameter (for the same material and technological process). The density parameter is significant for systems cushioning with regard to weight and cost constraints. The behavior of flexible foams was studied with density as the variable parameter in a range of 100–240 kg/m^3, with constant geometrical dimensions, for a wide range of drop heights and masses. We used the similarity parameters approach to predict the characteristics of the foams for various foam densities. The results show that for particular tested cases, the maximum deformation, the maximum deceleration, and the time pulse-period decrease as the foam density increases.

INTRODUCTION

In Part I[1] we have formulated the mathematical model, based on dimensional similarity parameters, to describe the characteristics of flexible plastic foams under impact conditions. The model assumes that the foam is a rate-dependent material. By using this model one can predict the maximum deformation, the maximum deceleration, and the time-pulse period for a wide range of drop heights and masses by conducting a few drop tests.

The designer of a protective packaging should choose the proper foam for specific needs. This means choosing the shape and the density of the foam for absorbing the shock of a known mass, while ensuring maximum permissible deceleration and deformation.

The characteristics of flexible foams under impact conditions are strongly dependent on their initial density for the same material and technology processes. The variation of the density of the flexible foam for the same geometrical dimensions affects the dynamic response, i.e., the cushioning parameters.

For rigid and semirigid foams it was reported[2] that the dynamic stress increases as the density of the foam increases. Therefore, a proper choice of the foam, for specific needs, for optimal cushioning performance (static and dynamic purposes) includes the proper choice of the shape and the initial density. It is clear that other parameters affect their foam characteristics, but, for foams made by this process and with the same technology, the density parameter has a special significance.

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Journal of Applied Polymer Science, Vol. 38, 1347–1356 (1989)
 CCC 0021-8995/89/071347-10$04.00

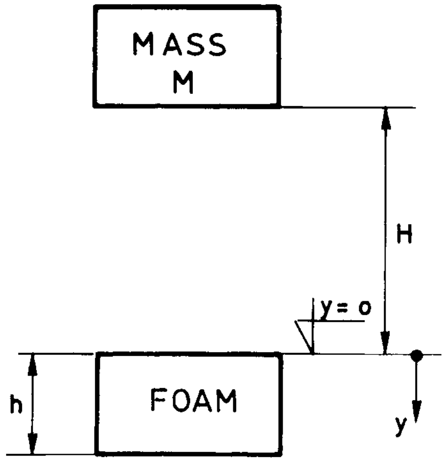

Fig. 1. A mass M dropped from height H on the foam of initial thickness h.

The aim of the present work is to predict the maximum deformation, maximum deceleration, and the time pulse period under test conditions for a wide range of foam densities. In the present work, we have extended the similarity model by including the density of the foam in the analysis.

By using the similarity parameters,[1] only a few experiments should be needed to plot work curves for various densities and drop conditions for the same geometrical dimensions. (It is proved that it is not necessary to vary the geometrical dimensions, for predicting the characteristics of the foam.) For flexible foams, made from the same type of glued and compressed pieces with differing densities, the density parameter is the one that allows optimization in the choice of foams for a given geometry.

THEORY

A body of mass M is dropped from height H on foam of initial uniform density ρ_0, thickness h, and cross-sectional area A as shown in Figure 1. The force F that mass M exerts on the foam at the time of impact is:

$$F = M\frac{d^2y}{dt^2} + Mg \tag{1}$$

where y is a displacement of the contact surface between the foam and the mass and g is a gravity acceleration. We assume a constant foam cross-sectional area during impact. This assumption was shown experimentally to be quite accurate for a wide range of drop tests.

Introducing the displacement-strain relationship and its derivations as

$$y = h \cdot \epsilon, \qquad dy/dt = h \cdot d\epsilon/dt, \qquad d^2y/dt^2 = h \cdot d^2\epsilon/dt^2 \tag{2}$$

where ϵ is the strain in the foam.

Combining eq. (2) with eq. (1) gives

$$\sigma(\epsilon, d\epsilon/dt, \rho) = (\sigma_{st} \cdot h)(d^2\epsilon/dt^2/g) + \sigma_{st} \quad (3)$$

where the static stress σ_{st} is

$$\sigma_{st} = M \cdot g/A$$

where the normal dynamic compression stress σ is a function of the strain (ϵ), strain rate ($d\epsilon/dt$), and the foam density (ρ).

The initial conditions, at the time of impact, which satisfy eq. (3) are:

(a) The initial displacement is zero ($y|_{t=0} = 0$)
(b) The initial velocity (V_0) is equal to the velocity of the mass M at impact time:

$$V_0 = dy/dt|_{t=0}$$

Actually, in severe impact conditions, the second term of the right-hand side can be ignored in eq. (3),† because the dynamic stress to static stress ratio $\sigma(\epsilon, d\epsilon/dt, \rho)/\sigma_{st}$ is much higher than unity. Therefore, maintaining the same initial conditions and keeping a constant value for the term $\sigma_{st}h$, from eq. (3), yields one possible solution only.

Mathematically, one can write

$$\sigma(\epsilon, d\epsilon/dt, \rho) = C_1 \cdot (d^2\epsilon/dt^2/g) \quad (4)$$

where $C_1 = \sigma_{st}h$, with initial conditions

(a) $d\epsilon/dt|_{t=0} = C_2 \quad (C_2 = V_0/h)$

(b) $\epsilon|_{t=0} = C_3 \quad (C_3 = 0)$

(c) $\rho|_{t=0} = C_4 \quad (C_4 = \rho_0)$

where C_2, C_3, C_4 are initial parameters and ρ_0 is the initial foam density.

The similarity parameters are (a) $\sigma_{st}h$, (b) V_0/h, and (c) ρ_0 for the same numerical values; for similarity parameters, one can expect to obtain the same solution for eq. (4), that is, the same impact response in the drop test for the same flexible foam material.

As a result, one can assume that for the same numerical values for similarity parameters in the impact conditions, the same values may be obtained for (a) maximum deceleration, (b) maximum deformation, and (c) time pulse period, for the same flexible foam.

These three parameters are the most important dynamic compression characteristics of the foam.[3,4] Prediction of these parameters for specific

†To predict the characteristics of the foam for constant thickness h. It is not necessary to ignore the right term in eq. (3).

TABLE I
Tested Foam Densities[a]

Specimen no.	Initial foam density ρ_0 (kg/m^3)
1	100
2	120
3	150
4	240

[a] The cross-section geometry is circular.

design is very useful for proper choice of the dimensions and the density of the foam.

One can apply this model by making several drop tests with various masses and drop heights, for the same plastic foam material and geometrical dimensions. (It is not necessary to use various geometrical dimensions to predict the dynamic characteristics of the foam.[1])

EXPERIMENTAL

Material

A total of four locally manufactured polyurethane flexible foams were tested. Each had a thickness of 0.2 m, and cross-section area of 0.272 m^2, but each had a different initial density. The production of different density foams is achieved by glueing together pieces of the same open-cell size (average cell size 0.5 mm) while applying different pressures. The foams were supplied by courtesy of Caesarea Polymers Ltd. (Or-Akiva, Israel). The data of the foams are shown in Table I.

Apparatus and Procedure

The experimental apparatus, shown schematically in Ref. 1, consisted of a changeable mass (of up to 60 kg) guided by eight rollers on a vertical guiding rod, which was 50 mm in diameter and 4.5 m long. The mass is positioned at the desired height H by an electrical winch and the foam is positioned at the bottom of the rod.

The deceleration pulse is measured by a piezoresistive accelerometer, and the deformation is measured by a photosensor with 0.5-mm resolution. The impact velocity V_0 is measured at the moment of impact contact time at $y = 0$ state by the photosensor. The measurement of the velocity V_0 is preferred to the drop height H, to eliminate the friction forces between mass and the guides.

In the present experiments, a TV camera was used to display the shape of the foam at impact time and, occasionally, to check the foam–mass contact time (in addition to the impact time being obtained from the output of the photosensors). The tests were conducted with different masses and drop heights for each foam.

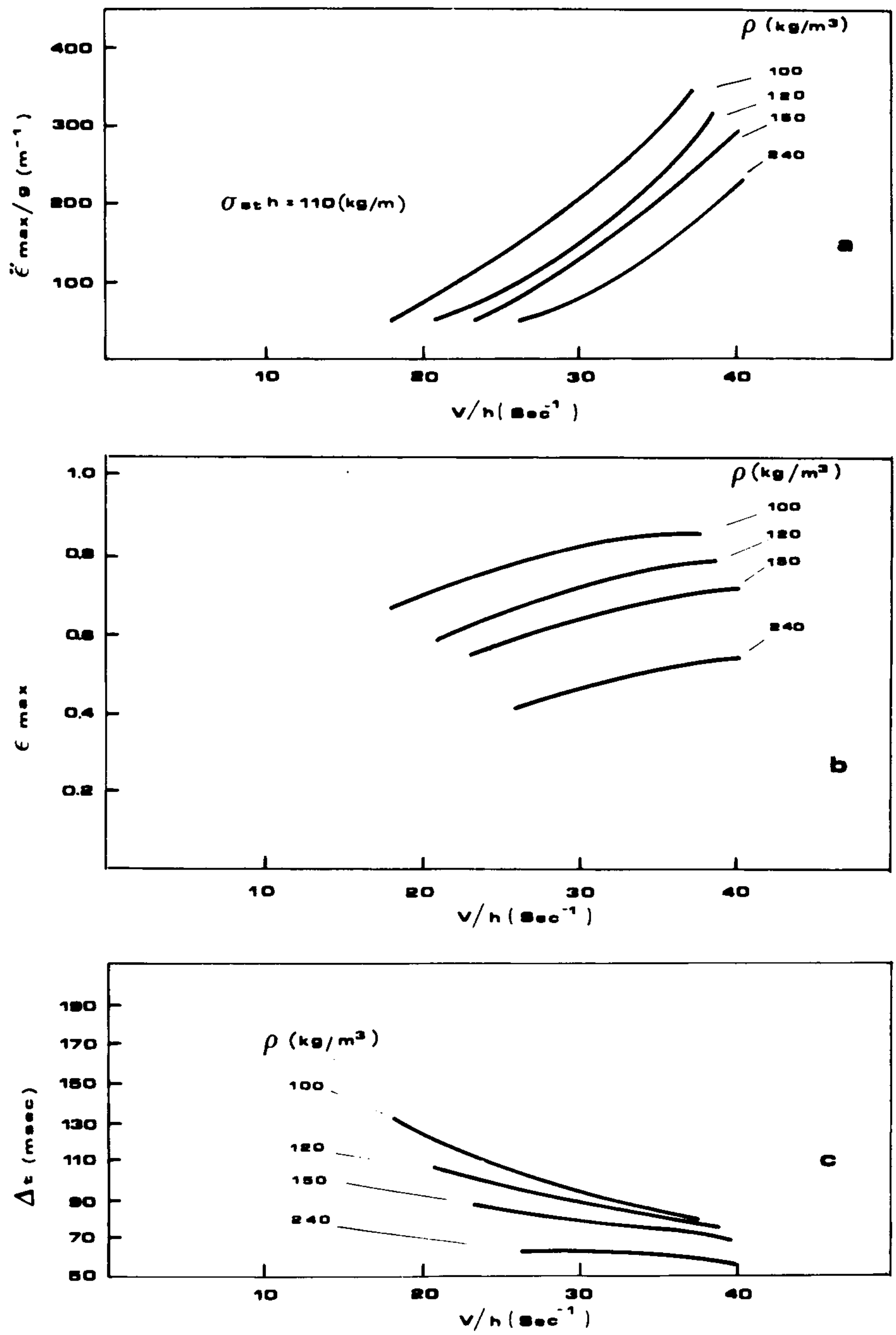

Fig. 2. Plot of (a) maximum deceleration, (b) maximum deformation, (c) time pulse period vs. V_0/h, for four different foam densities for $\sigma_{st} h$ = 110 kg/m.

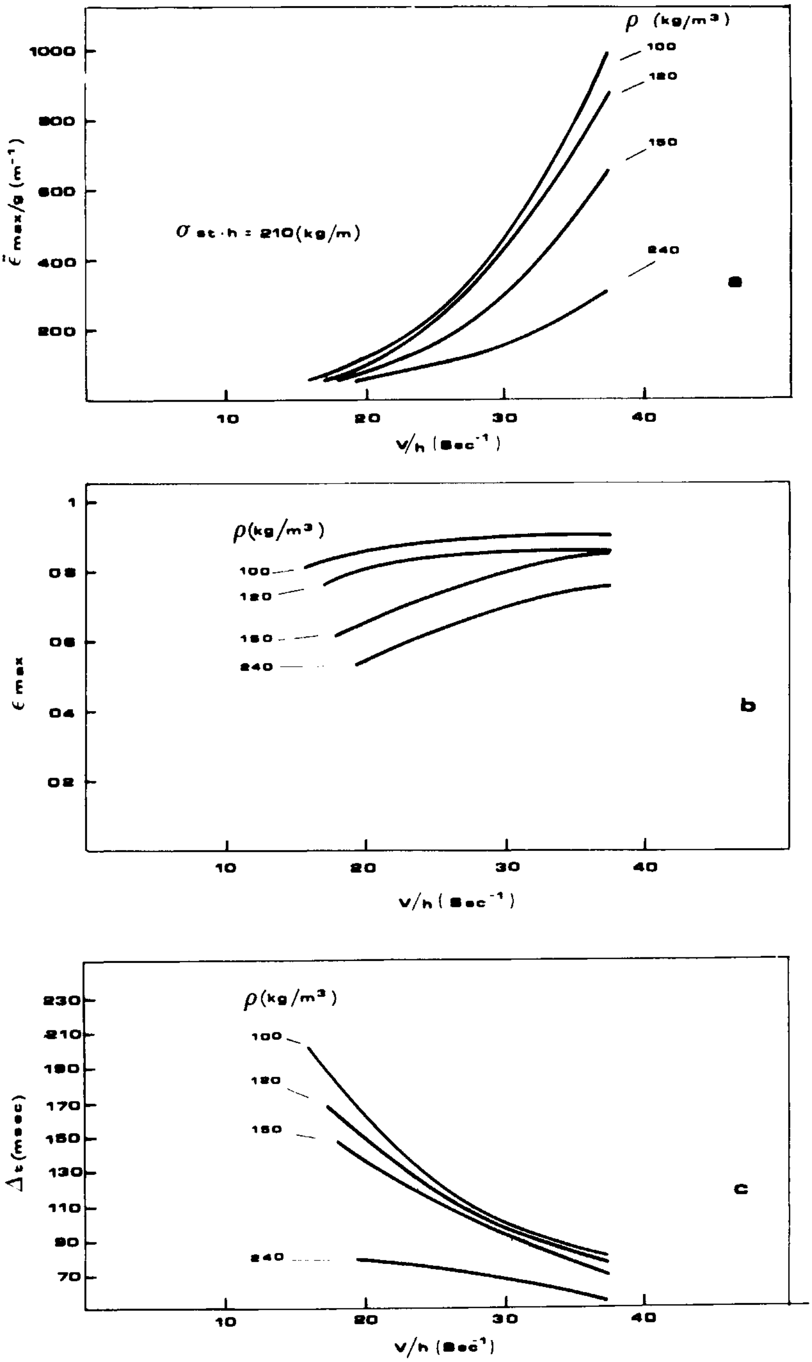

Fig. 3. Plot of (a) maximum deceleration, (b) maximum deformation, (c) time pulse period vs. V_0/h, for four different foam densities for $\sigma_{st} h = 210$ kg/m.

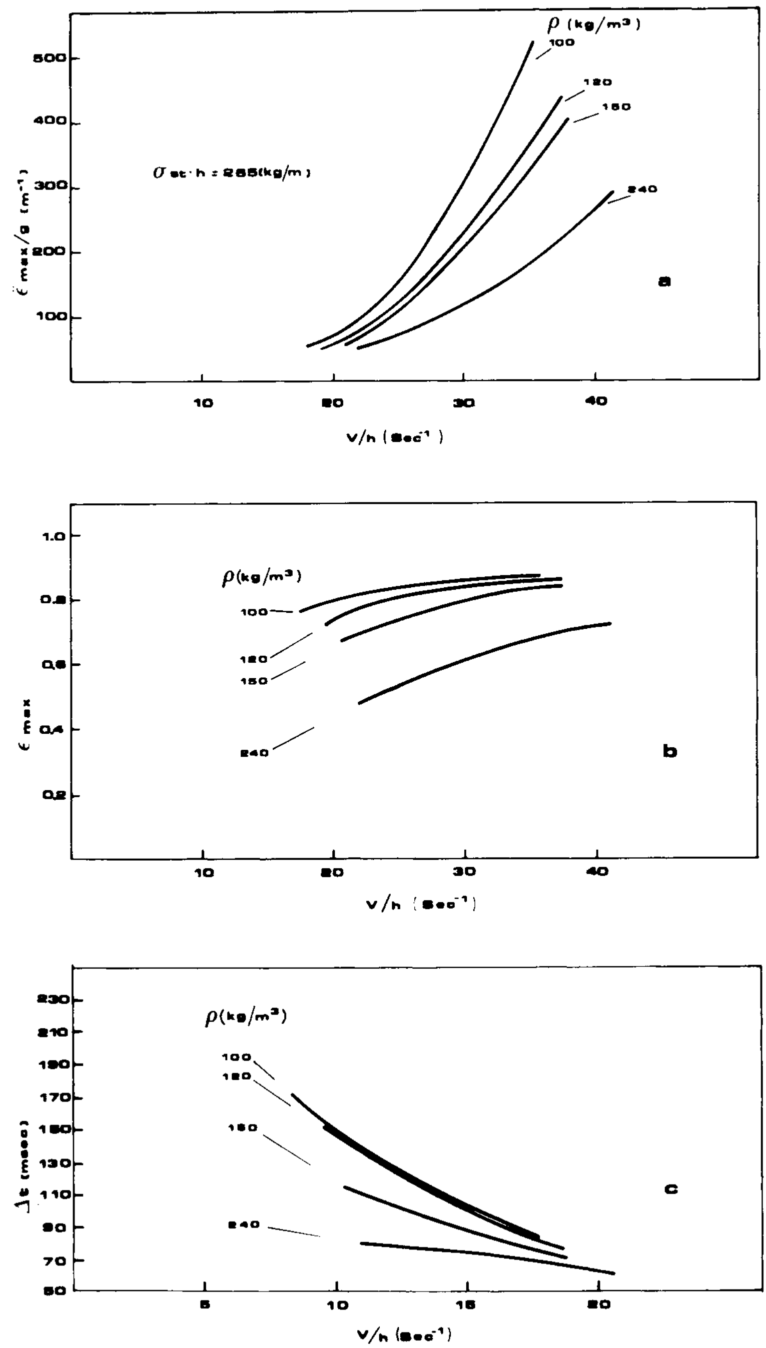

Fig. 4. Plot of (a) maximum deceleration, (b) maximum deformation, (c) time pulse period vs. V_0/h, for four different foam densities for $\sigma_{st}h = 265$ kg/m.

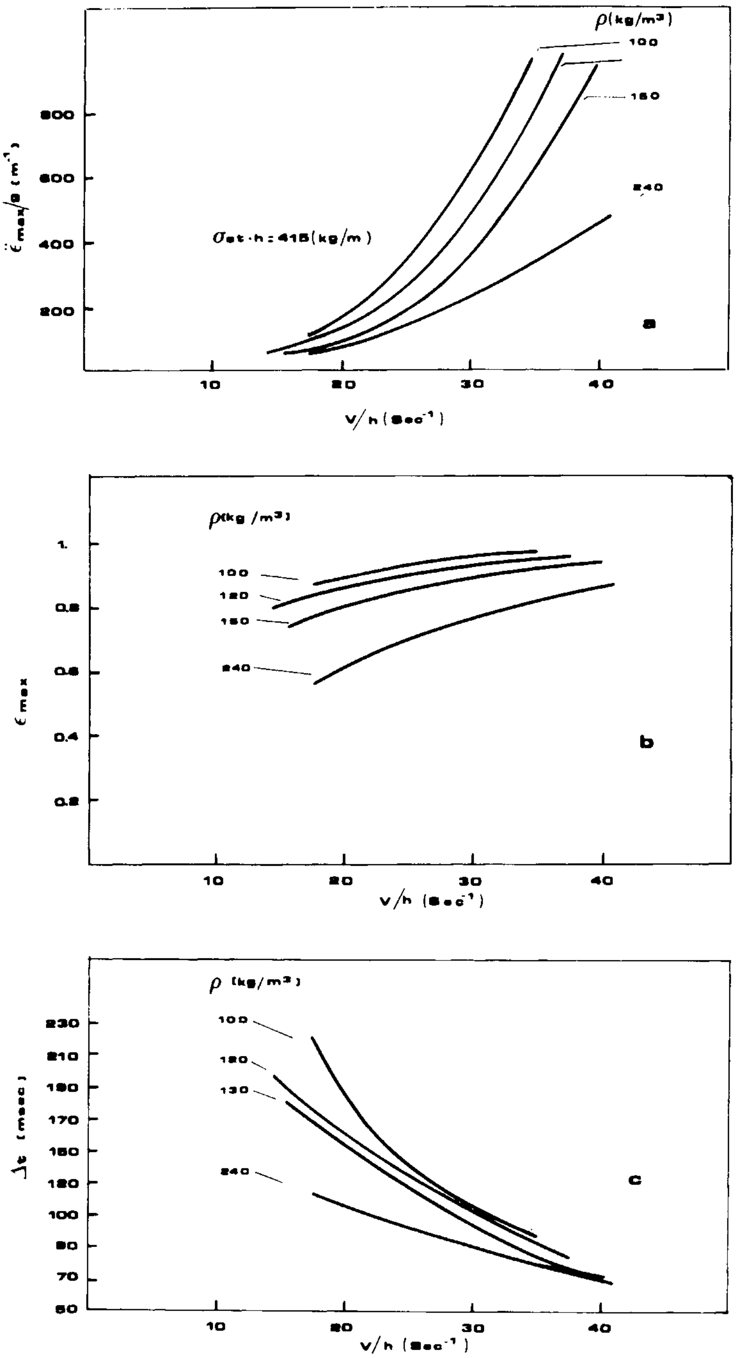

Fig. 5. Plot of (a) maximum deceleration, (b) maximum deformation, (c) time pulse period vs. V_0/h, for four different foam densities for $\sigma_{st} h = 415$ kg/m.

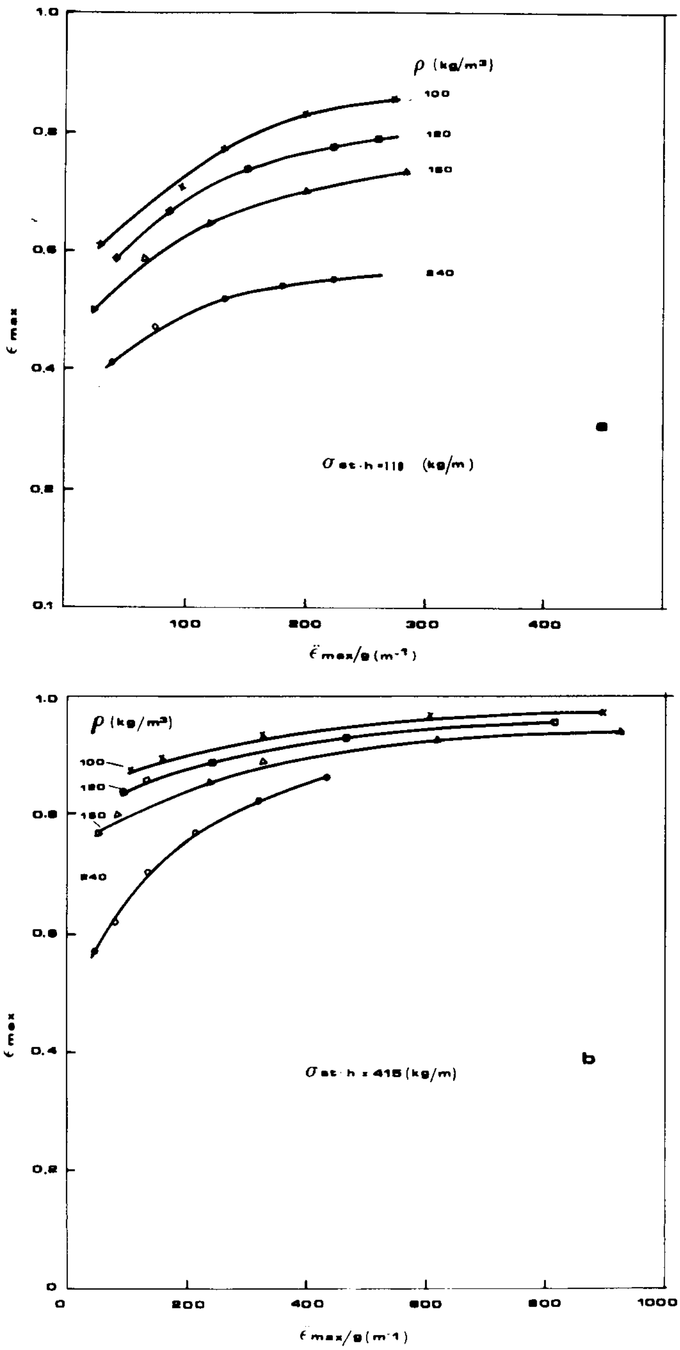

Fig. 6. Plots of maximum deformation vs. maximum deceleration for four different foam densities where: (a) $\sigma_{st} h$ = 110 kg/m; (b) $\sigma_{st} h$ = 415 kg/m.

RESULTS

Figures 2–5 show typical plots of (a) maximum deceleration $d^2\epsilon/dt^2/g$, (b) maximum deformation ϵ_{max}, and (c) time pulse duration Δt vs. V_0/h for different initial foam density (from 100 to 240 kg/m^3) for constant values of $\sigma_{st} h$. The experiment results were obtained for different drop heights H and masses M.

From the plots one can see that, as the foam density increases, all the three dynamic characteristic values increase consistently for the same impact conditions. It is a very interesting point that, for those specific tested density ranges, the results show that, as the foam density increases, the foam cushioning efficiency also increases, i.e., the maximum deceleration, maximum deformation, and the time-pulse period decrease. The typical plot of deceleration vs. time, under an impact condition, is different when the foam density varies. As the foam density increases, the peak pulse zone is more moderate.

Figure 6 shows a maximum deformation vs. maximum deceleration for (a) $\sigma_{st} h$ = 110 kg/m and (b) $\sigma_{st} h$ = 415 kg/m. This figure is predicted from Figures 2 and 5, respectively. As the deceleration rises sharply, the deformation increases moderately. This figure is a very useful plot for cushion designers to choose the proper flexible plastic foam for maximum permissible deformation and deceleration for goods under impact conditions.

In our work, we used more tests than necessary to predict the typical plots, in order to verify the simple mathematical model.

CONCLUSIONS

A simple mathematical model, based on dimensional similarity was extended to include the plastic foam density in the similarity parameters in order to enable more flexibility for the designer to choose the proper foam for cushioning goods. The model was presented and examined by drop tests with specially constructed apparatus. The results showed good correlation between the model and the experiments. The results show that the plastic foam density parameter is very significant in predicting the dynamic characteristics of the foam. This parameter makes available for more flexibility in the choice of foam.

For the whole range of foam densities tested the results show that, as the foam density increases, the maximum deformation, the maximum deceleration, and the time-pulse duration decrease.

By using the mathematical model, the designer can predetermine the dimensions for the foam and its density for maximum permissible deformation and deceleration (Fig. 6) for goods under impact conditions.

The support for this project by Caesarea Polymers Ltd. is highly appreciated.

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Received November 13, 1987
Accepted October 19, 1988