Compression of Cellular Plastics at High Strain Rates

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(Received February 17, 1970)

Introduction

The problems associated with protecting people from the hostile environments found in accidental situations are rapidly expanding as more and more information is gathered on the causes of accidental injury. The proper deployment of energy absorbing materials in the form of crash helmets, dashboard covers and collapsible steering columns have shown that significant improvements in human protection can be made. The problem of protection from impact exists in many phases of our everyday life, not just in transportation, but in the home and at work as well. The universality of the problem suggest that a basic approach be developed that would combine fundamental materials properties research on energy absorbing materials with the knowledge presently being created about human tolerance to impact.

Improvements in impact protection have been hampered by the lack of definitive information regarding the load-deformation properties of plastics which might be used for energy absorption. The bulk of the literature available to the designer has taken the form of stresses corresponding to single value of deformation and these values have almost always been reported from static loading tests. This paper defines the mechanical properties of a representative series of materials which were tested dynamically as well as statically thus giving the designer a more realistic information base to use in his material selection.

This paper was originally presented at the SPI Cellular Plastics Automotive Conference on February 24-26, 1970. As a Conference Paper, it has not been subjected to the Journal's normal review procedures but is reprinted here as a service to our subscribers.

Materials and Methods

The different materials investigated in this study are summarized in *Table I.* They were chosen because of their availability and for the fairly wide range of properties that they present. All of the materials tested were closed cell foams. Test specimens were rough cut from the sample block with a razor saw and then brought down to final dimensions by clamping them in a metal jig and sanding them on a belt sander taking care not to heat the specimen in the process. The final cross section of all the specimens was nominally a square, one inch on a side. The height of the specimens in all but one case was the received thickness of the sample slab. The test direction was always normal to the slab. The nominal height and density of the specimens of each material are listed in *Table I.* In all tests a minimum of three specimens of each material were used at each crosshead speed. The maximum deflection for each material

Table I. Material Summary.

MATERIAL AND CODE NUMBER		DENSITY LBS/FT^3	SPECIMEN HEIGHT IN.	INITIAL STRAIN RATE SEC^{-1}		
				SPEED 1	SPEED 2	SPEED 3
Polyethylene	E-1	2.34	2	0.17	17	100
Polyethylene	E-2	6.65	1.5	0.22	22	150
Polyethylene	E-3	9.05	2	0.17	17	100
Polystyrene	S-1	1.09	2	0.17	17	100
Polystyrene	S-2	3.35	2	0.17	17	100
Polystyrene (pelletized)	S-3	1.21	2	0.17	17	100
Polyurethane (rigid)	U-1	1.53	2	0.17	17	100
Vinyl	V-1	7.35	1	0.33	33	220
Vinyl	V-2	7.25	1	0.33	33	220
Vinyl	V-3	5.04	1	0.33	33	220
Cork	C-1	11.5	1.5	0.22	22	150

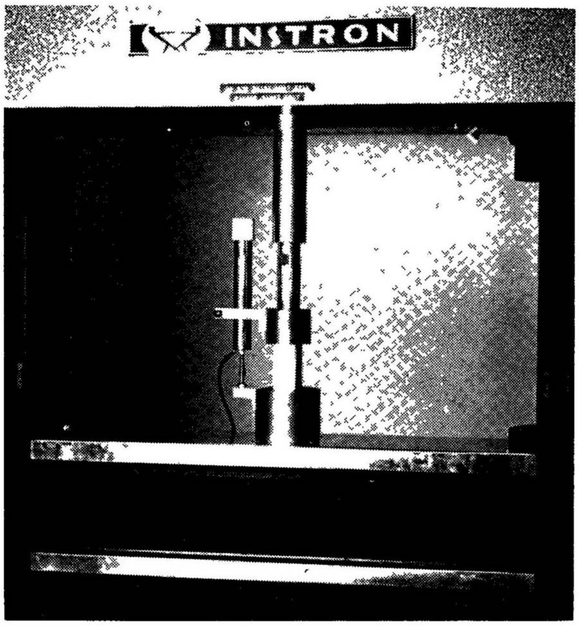

Figure 1. Compression test set-up in the Instron for the 20 inch/minute tests.

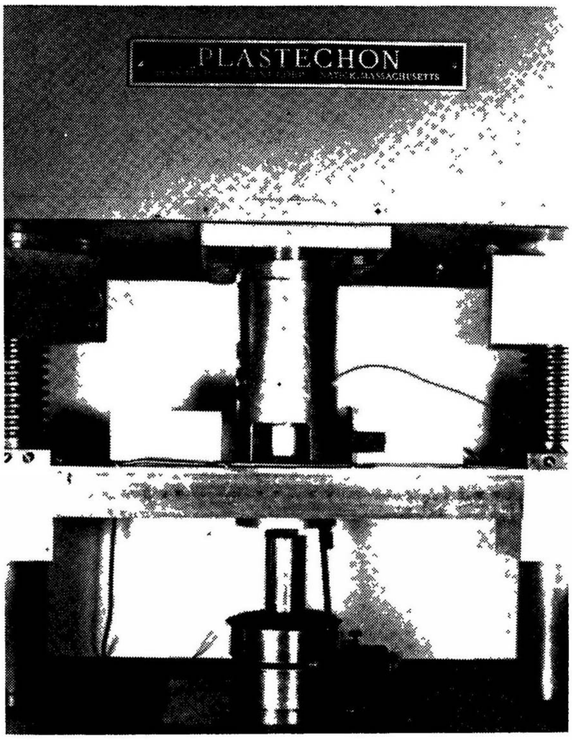

Figure 2. Compression test set-up in the Plastechon for the 2000 and 13000 inch/minute tests.

was adjusted to give a nominal 50% compressive strain. The crosshead speed was not changed to account for the gross height differences between materials so that the initial strain rates varied somewhat between materials as shown in *Table I.*

The static load-deflection tests on the materials were obtained on an Instron floor model testing machine using a crosshead speed of 20 inches per minute. The load was measured by an Instron strain gage load cell. The signal from the load cell was amplified using a Honeywell Accudata 104 Gage Unit and a 105 DC amplifier. The deflection of the specimen was measured by a Schaevitz 500 HR AC linear variable differential transformer. The test set up is shown in *Figure 1.* The signal from the LVDT was fed into the X-axis of a Tektronix 564 storage oscilloscope using a Tektronix 3C66 carrier amplifier. The load signal was displayed on the y-axis of the oscilloscope through a Tektronix 2A63 differential amplifier. The extension cycle feature of the Instron was used to load and unload the specimen automatically at a constant speed for one cycle. The resulting load-deflection curve was stored on the oscilloscope and then recorded as a photograph.

For the high speed tests a Plastechon high speed universal testing machine was used. Tests were conducted at nominal ram speeds of 2000 inches per minute and 13000 inches per minute. The 2000 inches per minute tests were performed with the machine in the closed loop mode. The load was measured with a Kistler 931A piezoelectric load cell with the specimen suspended from it with double sided tape. A Kistler 504 charge amplifier was used with the load cell and the signal was displayed as the y-axis on the oscilloscope using the 2A63 differential amplifier. The deformation of the specimen was measured by a linear potentiometer which is built into the testing machine and senses ram motion. As in the low speed tests the deformation was displayed as the x-axis against load on the oscilloscope. The test procedure was to fire the ram upwards at the specimen and then stop the ram mechanically by means of an adjustable sleeve to achieve the desired amount of deformation. The machine was then fired downward at the same rate to unload the specimen. The test apparatus configuration is shown in *Figure 2.*

For the highest speed testing the machine was used in the open loop mode. In this mode it was not possible to measure ram motion by the usual directly connected transducers. Instead, a phototransistorized optical device shown in *Figure 3* was used to obtain the displacement—time trace of the ram during a portion of the time the specimen was being crushed. This trace was used to calculate the ram velocity during the test. The load-time curve for the specimen was recorded on the oscilloscope and photographed. The load-time data was then converted to load-deflection data using the ram velocity information. The use of open loop mode in this test series also made it impossible to obtain the rapid unloading curves for the materials.

The data analysis performed on the results of the tests was concerned primarily with the specific energy absorption of the materials. The quantities which define the general energy absorbing characteristics of a material are the specific energy absorbed up to maximum strain (area A+B

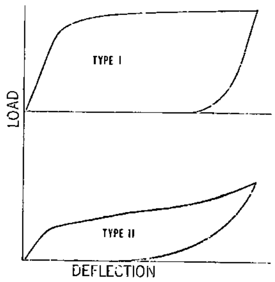

Figure 3. The two types of idealized load-deflection curves for the materials tested.

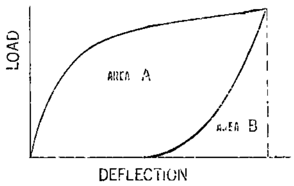

Figure 4. Idealized load-deflection curve showing the areas related to energy absorption and elastic recovery.

in *Figure 4* divided by the initial volume of the specimen) and the relative energy absorbing ratio (the ratio of area A to the area A+B in *Figure 4*). The quantities which are particularly pertinent to human tolerance are the stress levels imposed by the material as it deforms. The stress levels are directly related to the decelerations that the impacting person sustains. This stress level calculated from these tests was the stress at maximum load which in all but one case corresponded to maximum deflection.

Discussion of Results

The load-deflection curves produced by the materials in this study can be divided into two groups for ease of discussion as shown in *Figure 3*. *Table II* lists the materials with their curve types. The rigid polyurethane material U-1 is the only material which could not be strictly classified as to its curve type due to an initial high peak load spike followed by an abrupt collapse to a lower load level. The shape of the curve excluding the load spike was similar to a type I curve. In all the tests there was virtually no cross sectional dimension change up to maximum deflection thus the test can be considered to be a uniaxial strain test. Some buckling was evident in the 2 inch high specimens but it was during the latter part of the deflection and it did not appear to effect the load significantly. These tests were all conducted at constant crosshead velocities which, for many engineering materials, would constitute a constant strain rate test. However, due to the large deformations attainable with these materials, constant velocity does not mean constant strain rate. If the concept of instantaneous strain rate is applied it can be seen that the instantaneous strain rate will increase by a factor of two in achieving a strain of 50% compression. The initial strain rates are listed in *Table I*.

The results of over 100 tests are summarized in *Table II* and a plot of specific energy absorbed to

Table II. Test Results Summary.

MATERIAL	CURVE TYPE	AVERAGE MAXIMUM COMPRESSIVE STRAIN %	AVERAGE MAXIMUM STRESS PSI SPEED 1	SPEED 2	SPEED 3	AVERAGE SPECIFIC ENERGY ABSORBED TO MAXIMUM STRAIN IN.-LB/IN.[3] SPEED 1	SPEED 2	SPEED 3	AVERAGE RELATIVE ENERGY ABSORPTION RATIO SPEED 1	SPEED 2
E-1	II	46	15.8	20.2	21.8	4.42	6.4	7.0	0.48	0.69
E-2	II	48	59.8	60.5	77.7	20.9	19.9	29.2	0.76	0.87
E-3	II	45	86.2	107.1	132.0	28.9	37.6	45.2	0.82	0.90
S-1	I	46	47.2	48.5	49.7	19.8	20.7	21.2	0.86	0.87
S-2	I	45	141.1	177.5	175.4	57.1	71.0	72.7	0.93	0.95
S-3	I	46	34.7	37.0	37.7	11.6	12.1	12.2	0.82	0.85
U-1	I*	47	36.8	41.2	42.0	13.2	13.0	14.0	0.97	0.98
V-1	II	54	18.7	34	49.0	4.2	9.6	14.0	0.39	0.66
V-2	II	52	22.9	43.5	60.4	5.9	13.6	18.3	0.50	0.70
V-3	II	51	24.6	44.2	55.9	7.2	16.3	20.4	0.62	0.75
C-1	I	50	364.5	382.8	445.3	124.3	152.6	171.2	0.87	0.87

Note Speed 1 = 20 in./min Speed 2 = 2000 in./min Speed 3 = 13000 in./min

* Exhibited initial load spike.

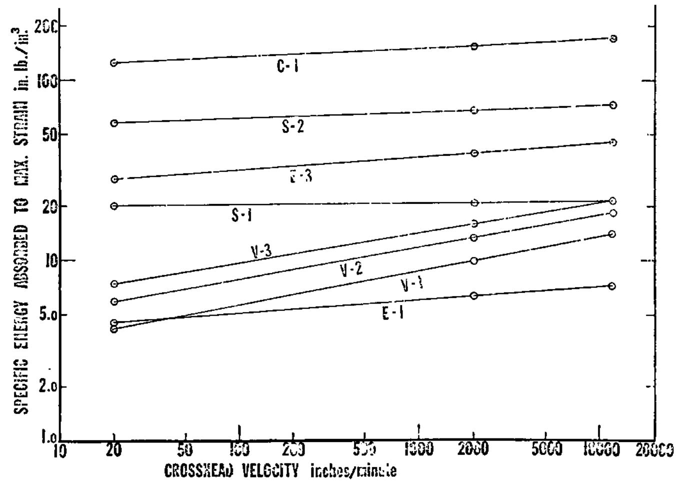

Figure 5. Specific energy absorbed to maximum strain versus crosshead velocity.

maximum strain versus crosshead velocity for some of the materials is shown is *Figure 5*. In general all the materials exhibited some response to strain rate. The polystyrenes and the polyurethane were the least sensitive showing a slight increase in stress level and energy absorption in the most dense specimens (S-2). The polyethylene foams exhibited what could be considered a mild rate sensitivity with an increase of about 50% in energy absorbing capacity at the highest test speed. The vinyl foams were the most spectacular in terms of their rate effects. The specific energy absorbed at the highest test speed was three times as great as the lowest speed value for all three types of vinyl. Increasing the density of a material increased the stress levels and the specific energy absorbed in all the materials with the exception of the vinyls. Here the effect was exactly reversed. The relative energy absorption ratio showed at the two lower speeds that the materials tended to improve their ability to absorb energy at the test speed increased.

It should be noted that the cork material (which was solid cork, not ground up) was an effective energy absorber but it created high stress levels.

Conclusions

A variety of foams have been studied which exhibit specific energy absorption properties that range from below 5 in-lbs/in³ to over 100 in-lbs/in³. The majority of the foams do not exhibit marked increases in properties with increasing test speed with the exception of the vinyl foams which exhibit dramatic increases.

The series of constant velocity tests reported in this paper is the initial step in creating a fundamental approach for defining the ideal energy absorber relative to human impact protection.

Acknowledgments

The authors wish to thank the Dow Chemical Company and Uniroyal for supplying the materials used in this study. The technical assistance of I. Barodawala, J. Warden, C. Gulash, G. Person and C. Dunn is also appreciated.

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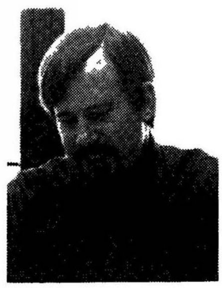

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