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EFFECT OF LOW AND INTERMEDIATE STRAIN RATES
ON THE COMPRESSIVE STRENGTH OF CELLULAR
CARBON AT THREE DENSITY LEVELS

MASTER

R. E. Oakes, Jr.

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NUCLEAR DIVISION
OAK RIDGE Y-12 PLANT

operated for the **ATOMIC ENERGY COMMISSION** under **U. S. GOVERNMENT** Contract W-7405 eng 26

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Nuclear Division

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ABSTRACT

Cellular carbon in the unbonded state at nominal density levels of 0.05, 0.10, and 0.22 gm/cc has been tested in compression, both parallel and normal to the direction of cell rise, at strain rates between 1.7×10^{-5} and 50 in/in-sec. Effects of the strain rate on the ultimate compressive strengths have been determined.

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SUMMARY

Cellular carbon is being developed for its elevated-temperature inertness and stability, and its high strength-to-weight ratio qualities. Materials at three densities, 0.05, 0.10, and 0.22 gm/cc, have been tested in compression, both parallel and perpendicular to the direction of cell rise, at strain rates between 1.7×10^{-5} and 50 in/in-sec and were found to be slightly rate sensitive at the higher rates. The increase in strength at higher rates is attributed to the strengthening effect of entrapped gases.

INTRODUCTION

Environmental and performance requirements of a number of technological areas (eg, the aerospace industry) have created a need for many materials having unique properties. One such requirement is for a material that possesses a high strength-to-weight ratio combined with both chemical and physical stability at elevated temperatures. Since polyurethane and other organic-foam systems are prone to deteriorate and creep at elevated temperatures, they do not meet the second requirement; however, they do have a high strength-to-weight ratio. Carbon, on the other hand, is inert and stable at elevated temperatures, but normally is too dense for such applications. Development of cellular carbon has been undertaken to provide a material which combines the high strength-to-weight ratio of organic foams and the inertness and stability of carbon.⁽¹⁾

Production of carbon foam utilizes the techniques of organic-foam production combined with high-temperature carbonization techniques. Basically, a rigid polyurethane foam containing a partially polymerized polyfurfuryl alcohol resin is carbonized in an inert atmosphere at 1,000° C. The cellular structure is derived from the cellular form of the polyurethane foam, and the thermosetting polyfurfuryl alcohol resin provides cell support and yields a higher carbon content than could be obtained from polyurethane foam alone. The density of the final product is controlled by varying the amount of water added to the basic polyurethane mixture prior to foaming. During the foaming process, the cells elongate in the direction of rise resulting in a material which exhibits anisotropic properties.⁽²⁾

The objective of this study was to determine the effect of strain rate on the anisotropic ultimate compressive strengths of carbon foams.

EFFECT OF STRAIN RATES ON COMPRESSIVE STRENGTH OF CELLULAR CARBON

EXPERIMENTAL METHOD

The specimen configuration used for all tests was a two-inch cube with the faces machined parallel to within 0.003 inch. Each sample was measured and weighed for density determination. The average density and observed variation range for each of the three materials was 0.051 ± 0.006 gm/cc, 0.100 ± 0.005 gm/cc, and 0.215 ± 0.015 gm/cc. All specimens for a single density group were taken from the same casting from which the outer edges had been removed in order to eliminate any edge defects. These specimens were tested in the free or unbonded condition without the addition of end or side stabilization. The type of test which is most applicable for the material, free or bonded, depends upon the end use of the material. If the material was used as a filler to support a component in the unbonded state, impact energy would be absorbed by sacrificing a layer of material; in the bonded state the design would have to be such that the ultimate strength is never exceeded if catastrophic failure is to be prevented.

Low-strain-rate compression tests (1.7×10^{-5} to 1.7×10^{-2} in/in-sec) were made on an Instron 10,000-pound-capacity universal testing machine. Load was measured with a strain-gage-type load cell and was recorded on a strip chart recorder as a function of the crosshead displacement.

The intermediate-strain-rate compression tests (5 to 50 in/in-sec) were performed on a Materials Testing System (MTS) testing machine. This equipment is composed of an electrohydraulic closed-loop, servo-controlled system with a maximum ram velocity of 12,000 in/min at 10,000 pounds force. A single hydraulic locking alignment grip with a spherical seating surface was used to provide proper platen alignment for these tests. Load was measured with a Kistler piezoelectric load cell and was photographically recorded on an oscilloscope as a function of ram displacement.

The strain rate for all tests is defined as the crosshead or ram velocity divided by the original specimen thickness, although it is realized that beyond the elastic region the material does not strain uniformly in the unbonded condition. Hence, the strain rate represents the average strain rate for the specimen.

DISCUSSION

Figures 1 through 6 show the effects of varying strain rates on the ultimate compressive strengths of 0.05, 0.10, and 0.22 gm/cc, nominal-density, unbonded carbon foams in directions both parallel and perpendicular to the direction of cell rise. Three tests were made for each material density at each strain rate considered, and the solid

Figure 1. ULTIMATE COMPRESSIVE STRENGTH AS A FUNCTION OF THE STRAIN RATE. (0.05 gm/cc Nominal Density Carbon Foam Parallel to the Direction of Cell Rise)

line on each figure was drawn through the average ultimate compressive strength at each strain rate. The band of variation between ultimate compressive strengths for the samples can be primarily attributed to sample density variations. For instance, the density range of the 0.05 gm/cc material is ± 0.006 gm/cc; the increase in compressive strength per unit density increase at 0.05 gm/cc density is 1,670 psi/gm/cc. Therefore, the expected variation in ultimate strength due to density variations would be about $(\pm 0.006 \text{ gm/cc}) \times (1,670 \text{ psi/gm/cc}) = \pm 10 \text{ psi}$, assuming that there are no density variations within the sample. Density variations within the sample would increase this band of variation even more. A similar analysis for the 0.1 and 0.22

Figure 2. ULTIMATE COMPRESSIVE STRENGTH AS A FUNCTION OF THE STRAIN RATE. (0.05 gm/cc Nominal Density Carbon Foam Perpendicular to the Direction of Cell Rise)

Figure 3. ULTIMATE COMPRESSIVE STRENGTH AS A FUNCTION OF THE STRAIN RATE. (0.1 gm/cc Nominal Density Carbon Foam Parallel to the Direction of Cell Rise)

gm/cc materials indicated that density variations could cause ultimate compressive strength variations of ± 25 and ± 180 psi, respectively.

Both the 0.05 and 0.1 gm/cc unbonded foams were observed to fail progressively at one or occasionally both of the load-bearing surfaces for all strain rates considered. The 0.22 gm/cc unbonded foam was also observed to fail progressively at the load-bearing surfaces until a 10 - 30 percent deformation was reached, after which the remaining material usually failed in an abrupt, brittle manner.

Figure 4. ULTIMATE COMPRESSIVE STRENGTH AS A FUNCTION OF THE STRAIN RATE. (0.1 gm/cc Nominal Density Carbon Foam Perpendicular to the Direction of Cell Rise)

Figure 5. ULTIMATE COMPRESSIVE STRENGTH AS A FUNCTION OF THE STRAIN RATE. (0.22 gm/cc Nominal Density Carbon Foam Parallel to the Direction of Cell Rise)

The average percent deformation at which each material was observed to exhibit the maximum compressive strength is shown in Table 1. Values are given for both the parallel and perpendicular directions. The scatter in percent deformation at the ultimate compressive stress was so great that no attempt was made to correlate the percent deformation at the maximum stress with strain rate. These relatively large values of deformation at the ultimate strength are in marked contrast with results which are obtained when the material is bonded between plates and tested. As an example, 0.05 gm/cc carbon foam typically fails catastrophically at less than one percent strain when bonded to the end plates; unbonded 0.05 gm/cc carbon usually does not reach its maximum strength until about 20 percent deformation has occurred.

Figure 6. ULTIMATE COMPRESSIVE STRENGTH AS A FUNCTION OF THE STRAIN RATE. (0.22 gm/cc Nominal Density Carbon Foam Perpendicular to the Direction of Cell Rise)

None of the three densities shows any significant variation in ultimate compressive strength over the strain-rate range of 1.7×10^{-5} to 5 in/in-sec. At 5 in/in-sec and above, a slight increase is observed, and this increase is more pronounced for the lowest density material. At the low strain rates, the primary failure mechanism is brittle failure. In the absence of viscous flow, this failure mechanism would not be expected to be rate sensitive. At the higher rates, gas entrapped in the cellular structure appears to provide some strength increase, possibly by pneumatically redistributing some of the stress to a shearing mode and by providing pneumatic support in the cellular structure. The lowest density material, containing more entrapped gas and having the weakest cellular structure, shows the effect of this pneumatic support to a greater extent than the higher density materials.

Table 1
PERCENT DEFORMATION AT ULTIMATE STRESS

Nominal Density (gm/cc)	Parallel to Rise (%)	Perpendicular to Rise (%)
0.05	20.4	16.5
0.10	12.1	10.1
0.22	8.6	7.4

The lowest density material also shows the greatest difference between the parallel and perpendicular compressive strengths. The ultimate compressive strength should be related to the amount of material per unit area that is normal to the direction of applied stress. The ratio of material per unit area in the parallel direction to that in the perpendicular direction is approximately equal to the ratio of minor to major axes of the average cell. (Visual observation indicates that the cells are ellipsoidal in shape.) Typical axis dimensions for the cells found in 0.05 gm/cc foam are 0.28 and 0.44 millimeter. Similar dimensions for 0.22 gm/cc foam are 0.18 by 0.23 millimeter. (2) Ratios of mass per unit area thus determined are 0.64 and 0.78 for the 0.05 and 0.22 gm/cc densities, respectively. Corresponding ratios of the average compressive strengths in the parallel and perpendicular directions are 0.60 and 0.82, in good agreement with the values of mass per unit area. Thus, it can be seen why the anisotropy becomes more pronounced at the lower densities.

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