TECHNICAL REPORT NO. 6-763

SHOCK-ABSORBING MATERIALS

Report 1

BACKPACKING MATERIALS FOR DEEPLY BURIED PROTECTIVE STRUCTURES

by

G. C. Hoff

March 1967

Sponsored by

Defense Atomic Support Agency

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U. S. Army Engineer Waterways Experiment Station
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ABSTRACT

The objective of this study was to review the existing theory and concepts pertaining to the use of backpacking materials around deeply buried protective structures and to provide a limited evaluation of a number of commercially available products in order to determine their suitability for use as backpacking.

The basic theory, concepts, and applications pertaining to the use of backpacking around buried structures were compiled and are reviewed. Based on the premise that a one-shot, one-material backpacking system will be adequate for the requirements of a deeply buried structure, a number of backpacking design considerations were established.

A cursory examination and review were given to 42 materials from 9 groups of materials to determine their practicality for use as backpacking. The groupings of materials by types include: granular materials, honeycombs, low-density concretes, flexible and rigid foamed plastics, and foamed rubber, glass, metal, and sulfur. None of the materials investigated and reviewed appear to satisfy all of the design considerations established for a backpacking material; however, this does not discount their being used as backpacking. The ultimate selection of a backpacking material should depend on the actual service conditions the

material will be subjected to, and these conditions may preclude some of the design considerations that the material in question cannot satisfy.

PREFACE

This study was conducted in the Concrete Division of the U. S. Army Engineer Waterways Experiment Station (WES) under the sponsorship of the Defense Atomic Support Agency (DASA) as part of Nuclear Weapons Effects Research Subtask 13.010, "Response of Buried Structures to Ground Shock." The work was accomplished under the general supervision of Mr. T. B. Kennedy, Chief of the Concrete Division, and under the direct supervision of Mr. J. M. Polatty, Chief of the Engineering Mechanics Branch, and Mr. W. O. Tynes, Chief of the Concrete and Rock Properties Section. Other staff members participating in the investigation were Messrs. Bryant Mather, R. L. Curry, Leonard Pepper, and G. C. Hoff. Mr. Hoff was project leader and prepared this report.

Directors of the WES during the investigation and the preparation and publication of this report were Col. Alex G. Sutton, Jr., CE, and Col. John R. Oswalt, Jr., CE. Technical Director was Mr. J. B. Tiffany.

CONTENTS

TABLES

FIGURES

NOTATION

a, b = displacements of cavity walls

A_r = end area of finite slice at original liner-backpacking interface

A_{ro} = end area of finite slice at original cavity wall-backpacking interface

E = modulus of elasticity

l = unit length

P_e = pressure at elastic yield point of the material

P_o = original pressure

p_l = varying component of packing pressure on liner

P_l = pressure at the locking state of the material

q = uniform component of packing pressure on liner

r = original radius of liner

r_o = original radius of cavity

t_f = thickness of backpacking

U_b = strain energy per unit volume of backpacking

U_{bt} = total strain energy capacity of backpacking volume, V_b

U_r = strain energy per unit volume of rock

U_{rt} = total strain energy capacity of rock core volume, V_r

V'_{av} = volume of additional voids in V'_v

V_b = volume of backpacking

V'_b = volume of finite backpacking slice

V_e = volume of material at elastic yield point

V_o = original volume

V_r = volume of rock core

V'_s = volume of solids in V'_b

V'_v = volume of voids in V'_b

V_l = volume of material at the locking point

y = deformation of liner

α = relative backpacking thickness

$\epsilon, \epsilon_1, \epsilon_2$ = strain

ϵ_b = required backpacking strain

ϵ_y = yield strain

π = 3.1416

σ = stress

σ_y = yield stress

$\overline{\sigma}$ = average stress

CHAPTER 1

INTRODUCTION

The applied forces for which a blast-resistant, deeply buried structure must be designed are transient in nature and their probability of occurrence is small. The magnitude of these forces depends on a number of factors over which a designer has no control. To eliminate some of the many unknowns imposed on the structural design of a buried structure, the designer may employ various structural systems in selected environments which will increase the probability of survival of the structure and its contents. One technique that can be used for controlling the magnitude of the forces being applied to a buried structure is the use of shock-absorbing backpacking materials around the structure.

1.1 OBJECTIVE

The general objective of the shock-absorbing materials program is to investigate existing materials and possibly develop new materials which could be satisfactorily used as shock-absorbing backpacking for deeply buried protective structures. The materials are to be investigated for desirable properties, including possible second-shot loading capability, availability, ease of handling and placement, and cost.

The objective of the first phase of this investigation was to review the existing theory for the application of backpacking materials and to provide a limited evaluation of a number of commercially available products in order to determine the suitability of certain types of materials as backpacking. This report describes this first phase.

1.2 SCOPE

To accomplish the objectives of the initial study of backpacking materials, a cursory examination and review were given to 42 materials from 9 grouping of materials by types to determine their practicality for use as backpacking materials. The types of materials include: granular materials, honeycombs, low-density concretes, flexible and rigid foamed plastics, and foamed rubber, glass, metal, and sulfur. In all cases when samples of the materials were available, the static stress-strain behavior of the materials was determined. When samples were not available, stress-strain curves for the materials in question were located in published reports. In some cases, additional properties and characteristics of the materials were also determined.

In addition, the basic theory, concepts, and applications pertaining to the use of backpacking materials around buried structures were compiled and are reviewed. This report will be limited to the premise that a one-shot, one-material backpacking system will be adequate for the protective needs of a deeply buried structure.

1.3 BACKGROUND

Interest in the use of backpacking for shock isolation of entire buried structures has generated many ideas as to the feasibility and composition of various systems and materials that could be satisfactorily used as backpacking. As early as 1953 it was suggested in Reference 1 that: "The space between the lining and the tunnel surface should be filled with a material of low density that will absorb the energy of the flying rock, distribute pressure from fallen rock, and provide a mismatch of acoustic impedance so that reflection will take place at the tunnel surface rather than at the surface of the lining."

The beneficial use of a frangible backfill in isolating and protecting underground structures in Operation Plumbbob from violent ground motions in their vicinity was reported in Reference 2. During Operation Plumbbob, vertical concrete pipes covered with concrete slabs were lined one layer thick on the sides and bottom with empty glass quart bottles. When compared with the control pipe for the experiment, which had soil backfilled directly against it, it was found that the peak accelerations produced by shear forces exerted on the sides of the isolated pipes were reduced to 26 percent of those of the control pipe. This reduction was attributed in part to the collapse and crushing of the glass which dissipated a portion of the shock energy.

In two related studies (References 3 and 4), various methods were employed on or about cylinders buried in silica sand in order to alleviate shock-induced motions of the cylinders. These methods consisted of: (1) wrapping the cylinders in flexible and rigid polyurethane foams, (2) using air voids between the sand and the cylinder, (3) using preexpanded polystyrene beads as a crushable backfill aggregate, and (4) using sands of varying densities as backfill aggregate separated from the overall bed by a stove pipe. It was concluded that polyurethane foams placed around a cylinder and other materials functioning as a loose backfill aggregate were effective in attenuating the response of the isolated structures. In a study on the influence of mechanical shielding on the response of buried cylinders (Reference 5), a crushable layer directly over the buried cylinder was introduced. The use of this crushable material greatly reduced the magnitudes of the loads reaching the cylinder.

In presenting theoretical descriptions of the propagation of a pressure pulse in a potential backpacking material, it was suggested in Reference 6 that foamed or distended materials are effective in reducing the peak pressures delivered to a structure when an impulse is applied to the opposite surface of the foam.

In discussing the methods of mitigating the effects of shock for lined tunnels in rock, it was stated in Reference 7 that the current design concept for protective liners in competent rock includes the provision for a highly deformable material between the face of the rock and the liner: "It would appear that the magnitude of...forces (generated by spall impacts) reaching the lining could be significantly reduced if a crushable material is introduced between the face of the rock and the lining."

In Reference 8 it was suggested that the shock energy reaching a buried structure in rock can be partially dissipated by (1) reflection of energy and (2) energy absorption; these actions can be enhanced by interposing a material between the structure and the confining medium that has a low shock impedance with respect to that of the confining medium. The impedance mismatch that occurs will cause some energy to be reflected. If the low shock impedance material is also very deformable under applied stresses, it will absorb the energy present in the form of ground motions and accelerations.

1.4 DESIGN CONSIDERATIONS

A review of the investigations cited above and other similar projects provides an insight to what is necessary in designing a backpacking system for shock-isolating purposes. In general, a suitable backpacking should be a frangible or crushable material possessing a low breaking or crushing stress level and a high degree of compressibility. The material should (1) dissipate and reflect a portion of the shock energy, thereby reducing the magnitudes of the forces reaching the structure, (2) limit the forces transmitted through the backpacking to the structure to a defined magnitude and range, and (3) accommodate the deformations of the cavity in which the structure has been placed.

In support of these three primary considerations, the material should also (4) possess a second-shot loading capability, (5) be resistant to age effects, (6) be resistant to the infiltration of groundwater, (7) be insensitive to strain-rate changes, (8) be readily available, (9) be easy to handle and place around a buried structure, and (10) be economical.

These secondary considerations are often as important as the three main considerations. A material that is only partially failed when subjected to a single-burst loading should be capable of exhibiting the same type of behavior for the remaining unfailed material when it is subjected to a second-burst loading. If it does not, the design of the structure will be further complicated. The material should also resist changes in mechanical properties with age and with straining rate as it would be difficult to design structures for continually varying behavior of the backpacking. The material must resist the infiltration of groundwater to ensure that the shock waves are not transmitted through a water medium to the structure. In keeping with item (10) (economy), the materials should be readily available in most areas and be easy to handle and place, thus reducing shipping and labor costs.

In satisfying one or all of the above considerations, it should be kept in mind that the ultimate selection of any material for use as backpacking should depend on the service conditions to which the material will be subjected and the final in-place cost of the material.

Because of the large relative costs of construction versus design overpressures (References 9 and 10), the scope of this investigation will be restricted to design overpressures less than 1,000 psi; that is, the magnitude of stress transmitted to the structure through the backpacking material will be less than 1,000 psi. Assuming single-burst loading where closure of the cavity is imminent, deformations of the backpacking to accommodate this closure should be approximately 50 percent.

CHAPTER 2

THEORY

2.1 PRESSURE-VOLUME, STRESS-STRAIN RELATIONS

Most of the materials that have been or are being investigated generally fall into two distinct categories: (1) materials having no distinct yield point and some degree of compressibility, and (2) materials possessing a distinct yield point plus some degree of compressibility. Ideally these materials can be represented by pressure-volume curves for a bilinear locking solid (Figure 2.1) and a linear-plastic-linear locking solid (Figure 2.2), respectively (References 6, 11, and 12).

Consider first the case of a bilinear locking solid (Figure 2.1). The original volume is designated V_o . Under a small applied pressure the specific volume decreases to V_1 at no appreciable increase in the pressure. At V_1 the material locks, with only small additional decreases in volume occurring for additional large increases in pressure.

In the case of the linear-plastic-linear locking solid (Figure 2.2), the initial specific volume is again represented by V_o . Under the application of pressure the material behaves as an isotropic elastic solid until P_e , the elastic yield pressure, is reached with V_e corresponding to the volume of the material at the elastic yield point of the material. The material then decreases in volume at no further increase in pressure until V_l , the locking point, is reached. Only large increases in additional pressure will cause additional small decreases in the volume after locking has occurred.

Under blast-loading conditions the loaded area is normally so great that the portion of the medium under consideration and its inclusions can be assumed to be laterally confined with displacements occurring only in the direction of loading. By applying this assumption of lateral restraint to the ideal pressure-volume curves, they can readily be converted to stress-strain curves for bilinear and linear-plastic-linear locking solids subjected to one-dimensional compression (Figures 2.3a and 2.3b). This conversion to a stress-strain relation provides a convenient tool for evaluating the energy-dissipating capability of the materials. To simplify the discussion of the bilinear and linear-plastic-linear locking solids throughout this report, they will hereafter be referred to as plastoelastic and elastoplastic materials, respectively.

2.2 ENERGY ABSORPTION

The energy absorbed by a material depends on two factors: (1) the deformation of the material, and (2) the forces in the material during the deformation (Reference 13). The product of the strain and the unit force results in the amount of energy absorbed by the material:

$$U_b = \overline{\sigma} \times \epsilon_b$$

$$= \text{area under the stress-strain curve (Figure 2.4)} \qquad (2.1)$$

U_b is expressed as the energy per unit volume of material and can be shown for all cases to be:

$$U_b = \int_0^{\epsilon} \sigma \times d\epsilon \qquad (2.2)$$

The total strain energy capacity, U_{bt}, of a given volume of backpacking, V_b, can then be expressed as

$$U_{bt} = V_b \times U_b \qquad (2.3)$$

Where U_b is strain energy per unit volume of backpacking.

Before proceeding, a distinction should be made between the terms energy absorbed and energy dissipated. Figure 2.5 represents a typical stress-strain curve for a material possessing elastoplastic properties. The entire shaded area represents the energy absorbed per unit volume by the material to a given strain ϵ_2. When the applied forces are removed from the material, some strain $(\epsilon_2 - \epsilon_1)$ may be recovered due to the elastic properties of the material. The energy regained during this recovery is known as rebound energy. The actual energy dissipated by the material then is equal to the absorbed energy minus the rebound energy (Reference 13), or

$$\text{Absorbed energy} = \text{dissipated energy} + \text{rebound energy} \qquad (2.4)$$

In general, the backpacking is assumed to be most effective when designed to have an energy-absorbing capacity equal to that of the core of material removed to form the cavity (Reference 14). This assumption is contingent on the fact that the structural system must have the proper strength and stiffness to develop the energy-absorbing capacity of the backpacking.

In determining the energy absorbed by the rock core, it is assumed that the rock, when subjected to a plane wave of stress, may behave either elastically or elastoplastically (Figure 2.6). The latter behavior is assumed (Reference 14). The strain energy in the rock for a free-field strain $\epsilon \geq \epsilon_y$ can then be expressed as:

$$U_r = \epsilon\sigma_y - \frac{1}{2}\sigma_y\epsilon_y \qquad (2.5)$$

where U_r is expressed as the strain energy per unit volume of rock, σ_y as yield stress, and ϵ_y as yield strain. For the elastic condition, $\epsilon < \epsilon_y$, the strain energy is:

$$U_r = \frac{1}{2}\sigma\epsilon \qquad (2.6)$$

or

$$U_r = \frac{1}{2} E\epsilon^2 \tag{2.7}$$

The total strain energy capacity, U_{rt} , of a given volume of rock, V_r , can then be expressed as

$$U_{rt} = V_r \times U_r \tag{2.8}$$

Based on the assumption that the energy-absorbing capacity of the backpacking should be equal to that of the core of material removed to form the cavity, Equations 2.3 and 2.8 can be equated:

$$U_{bt} = U_{rt} \tag{2.9}$$

or

$$V_b \times U_b = V_r \times U_r \tag{2.10}$$

2.3 THICKNESS DETERMINATION

The actual thickness of a backpacking should include: (1) the required strain (ϵ_b) to satisfy the energy-absorption requirements (Equation 2.10), and (2) the solid material volume and possible additional void content comprising the backpacking. Both of these requirements must also satisfy a third requirement, i.e., that the backpacking be sufficiently thick to provide enough clearance between the cavity wall and the structural system to accept rock motions (bulking and spalling)[1] without impacting the structural system (Reference 15).

The volume of backpacking (V_b) for any given barrel-type liner (Figure 2.7) can be expressed as:

$$V_b = \pi l \left(r_o^2 - r^2\right) \qquad (2.11)$$

Where: $\pi = 3.1416$

l = unit length

r_o = original radius of cavity

r = original radius of liner

The thickness of the backpacking (t_f) is then $r_o - r = t_f$, or

$$r = r_o - t_f \qquad (2.12)$$

Substituting Equation 2.12 into Equation 2.11, a different expression for V_b results:

$$V_b = \pi l \left[r_o^2 - (r_o - t_f)^2\right]$$

$$V_b = \pi l \left(2r_o t_f - t_f^2\right) \qquad (2.13)$$

---

[1] A reduction in diameter (of the cavity) occurs, arising from the fact that the rock is crushed and displaced around the outside of the cavity. In the process of doing so, it bulks and increases in volume, thereby decreasing the volume of the cavity (Reference 15).

If α represents the relative backpacking thickness and is expressed as:

$$\alpha = \frac{t_f}{r_o} \tag{2.14}$$

Equation 2.13 can be modified to appear as:

$$V_b = \pi r_o^2 l \; (2\alpha - \alpha^2) \tag{2.15}$$

or:

$$V_b = V_r \; (2 - \alpha) \; \alpha \tag{2.16}$$

where $\pi r_o^2 l$ is equal to the volume (V_r) of rock core the backpacking and liner are replacing.

Equation 2.10 in the preceding section can also be expressed as:

$$U_r = \frac{V_b U_b}{V_r} \tag{2.17}$$

By substituting the expression for V_b from Equation 2.16 into Equation 2.17, neglecting spatial distribution and higher order terms, an energy expression in terms of the relative backpacking thickness is derived:

$$U_r = U_b \; (2 - \alpha) \; \alpha \tag{2.18}$$

U_b , in Equation 2.1, was expressed as the product of the average force, $\overline{\sigma}$, and total strain, ϵ_b , in the backpacking:

$$U_b = \overline{\sigma} \times \epsilon_b \qquad (2.1)$$

By substituting this expression into Equation 2.18 and solving for ϵ_b , an expression for the total required strain in the backpacking is obtained:

$$U_r = \overline{\sigma}\, \epsilon_b\, (2 - \alpha)\, \alpha \qquad (2.19)$$

or

$$\epsilon_b = \frac{U_r}{\overline{\sigma}\, (2 - \alpha)\, \alpha} \qquad (2.20)$$

Equation 2.20 allows the average stress ($\overline{\sigma}$), total required strain (ϵ_b), and relative packing thickness (α) to be determined by trial-and-error procedures based on the total strain energy that would have existed in the core of the rock now occupied by the backpacking and a structural system. In the absence of actual free-field strain values for the media in question, procedures similar to those described in Reference 16 can be pursued to obtain a computed value for free-field strain.

The volume of any material is determined by the sum of the volumes of all of its constituents. In order to satisfy the energy-absorption requirement, the material in question must be very deformable at the crushing stress level of the material. This deformability is best achieved by ensuring that the material has a high void content. Once the material crushes, the voids will collapse and give the desired deformation.

By assuming that the total volume in question is a small radial slice of finite length of the backpacking as shown in Figure 2.7, such that the end areas of the slice (A_r and A_{ro}, at original liner- and cavity wall-backpacking interface, respectively) are approximately equal, $A_r \cong A_{ro}$, the composition of the backpacking slice can then be pictured as seen in Figure 2.8.

The total volume of the slice is V_b' and is composed of the volume of voids (V_v') and the volume of solids (V_s'). The volume of voids can be expressed as the sum of the voids ($\epsilon_b V_b'$) necessary to produce the required strain, ϵ_b, and any additional voids (V_{av}') remaining in the material after ϵ_b has been reached:

$$V_v' = \epsilon_b V_b' + V_{av}'$$

In practice, the additional voids (V_{av}') are necessary to provide additional deformations as the material departs from its constant or quasi-constant stress level and locks up (Figure 2.9). The additional voids may also be necessary to satisfy the third requirement for thickness determination, i.e., be thick enough to accommodate the rock motions (bulking and spalling) without impacting the structural system.

The total amount of voids in a potential backpacking material is unique to that material and within limitations can be varied to satisfy the total deformation requirements of a backpacking, provided the strength properties of the material containing the voids are similarly tailored to satisfy the crushing strength requirements of the backpacking.

No good theoretical solution to the problem of bulking and spalling exists; however, empirical expressions for rock-face displacements have been developed (Reference 17) and can be used for design purposes.

2.4 STRESS TRANSFER

When the closure of a cavity containing a backpacked liner is uniform, the deformation of the backpacking will also be uniform; if the backpacking is homogeneous and isotropic, the circumferential stress transferred to the structure will also be uniform. The magnitude of the load reaching the structure will depend on the load-deformation characteristics of the backpacking plus the amount of deformation occurring. If, however, the deformation or stress in the backpacking is nonuniform, the liner will tend to deform into an oval or elliptical shape as shown in Figure 2.10.

In a discussion of the factors to be considered in designing blast-resistant and ground-shock-resistant structures (Reference 15), this problem was approached by permitting the liner to deform to such an extent as to develop in the backpacking appropriate resisting stresses against the deformation. In this case, the liner must have requisite strength in compression and in buckling, and must be able to deform sufficiently without failure or fracture in order to develop the required resistance.

In developing the stress-transfer theory (Reference 15), a and b (Figure 2.10) were allowed to represent the displacement of the cavity walls. However, because of the deformations, y, of the liner, the net change in thickness of the backpacking at the sides is $b - y$ and at the top is $a + y$. By assuming a general situation of load deformation for an elastoplastic material (Figure 2.11), it can readily be seen that the magnitude of the net differential pressure between points b and a, assuming the liner does not deform, is much greater than the net differential pressure between points $b - y$ and $a + y$ when the liner does deform. If the loads at deformations $b - y$ and $a + y$ are expressed as $q + p_1$ and $q - p_1$, respectively, the average of these pressures is the uniform component of load, q, and the difference from the average is p_1, the inward or outward component of load. It is this component of load, p_1, which produces the elliptical or oval deformation of the liner. As can be seen from the ideal curve in Figure 2.11, the larger the net differential pressure is, the greater p_1 is. When p_1 is large, the deformations of the liner are large; when liner deformations are large, the backpacking is compressed more. This causes the pressure differential to become smaller, which in turn reduces p_1 and thus the deformations of the liner, until an equilibrium is reached at a uniform pressure q. If the deformations of the cavity are such that point b lies on the yield plateau of the load-compression curve for the backpacking, the maximum stress transferred to the structure will be equal to or less than the yield strength of the backpacking.

This same approach to stress transfer can be implemented using a load-deformation relation for plastoelastic materials but with a little more difficulty as it is relatively impossible for a liner interacting with the progressively increasing stress-strain relation of a plastoelastic material to develop a resistance characterized by a nearly uniform compression on all sides.

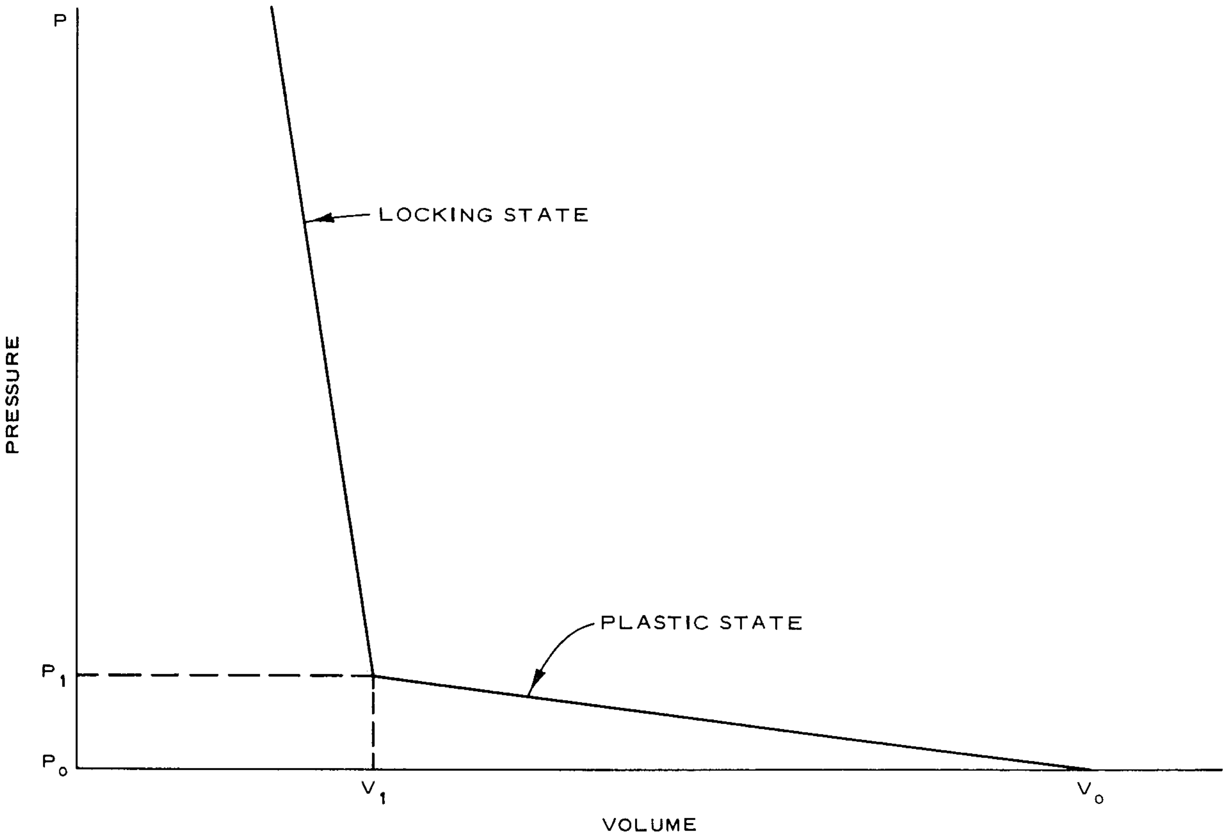


Figure 2.1 Pressure-volume relation for a bilinear locking solid.

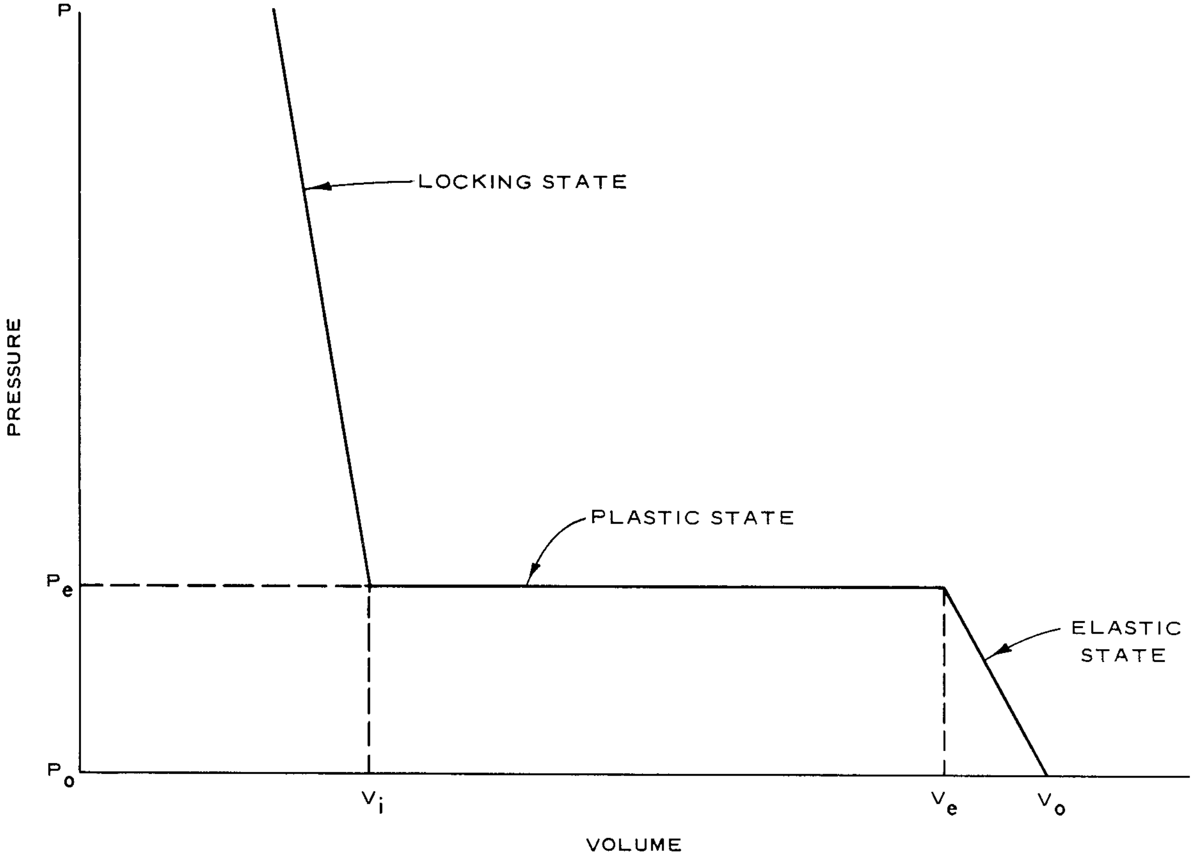
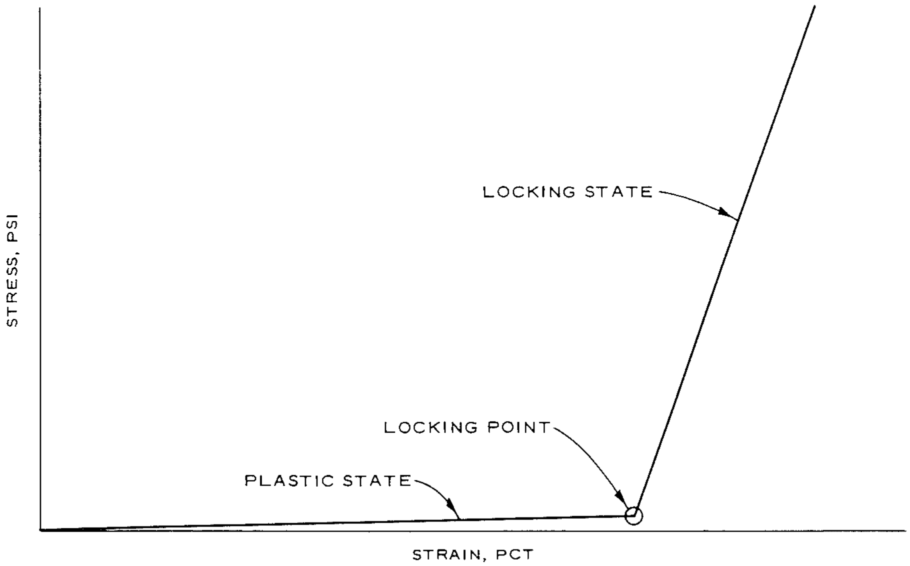
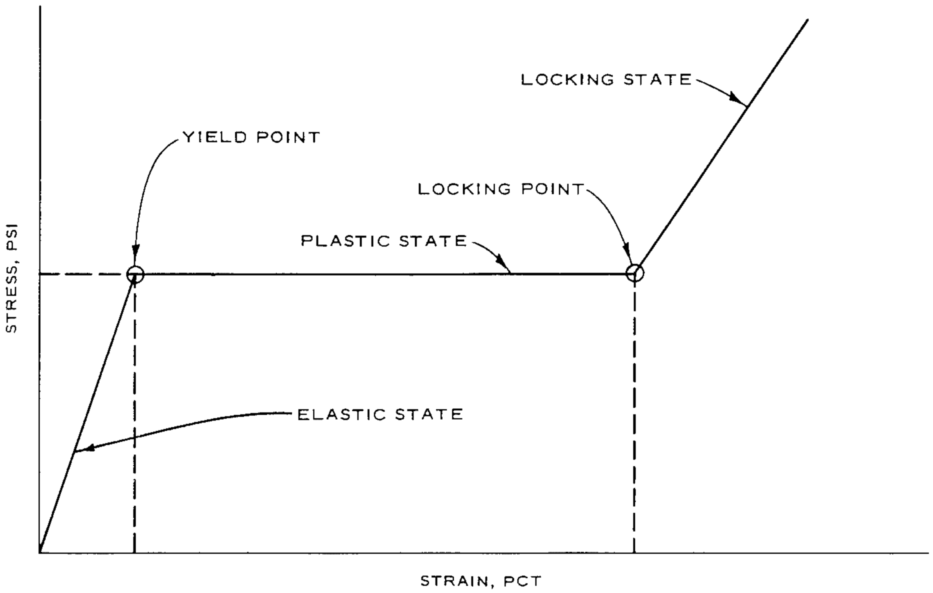


Figure 2.2 Pressure-volume relation for a linear-plastic-linear locking solid.

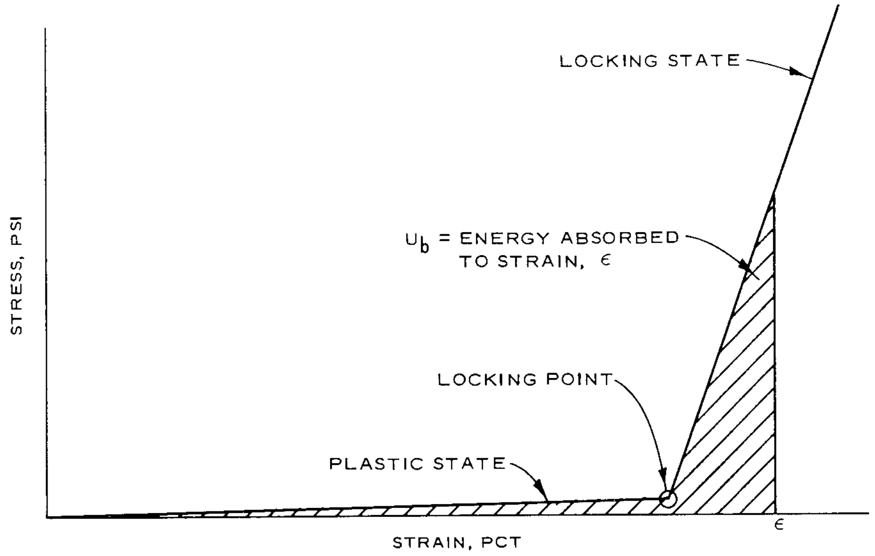


a. PLASTOELASTIC (BILINEAR) MATERIAL

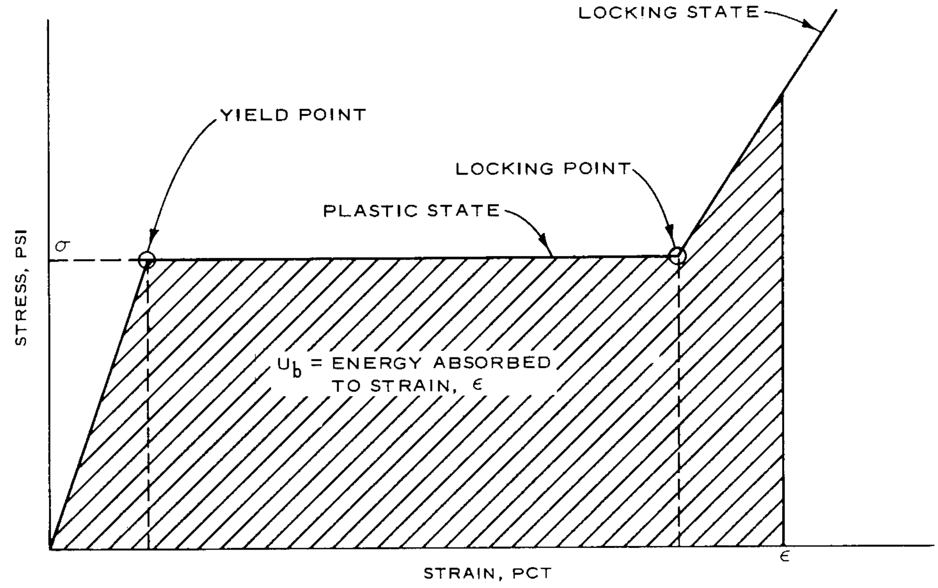


b. ELASTOPLASTIC (LINEAR-PLASTIC-LINEAR) MATERIAL

Figure 2.3 Ideal stress-strain relations.



a. PLASTOELASTIC MATERIALS



b. ELASTOPLASTIC MATERIALS

Figure 2.4 Ideal stress-strain relations showing energy absorbed to a given strain, ϵ .

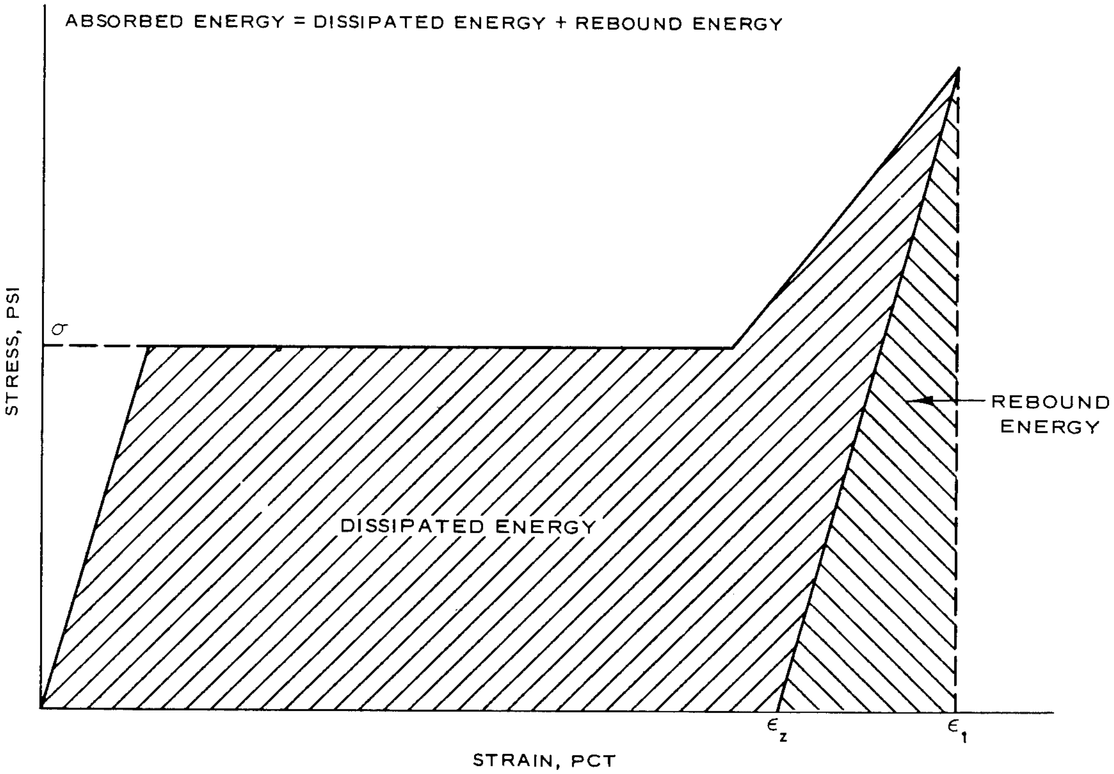


Figure 2.5 Ideal stress-strain relation showing absorbed energy, dissipated energy, and rebound energy.

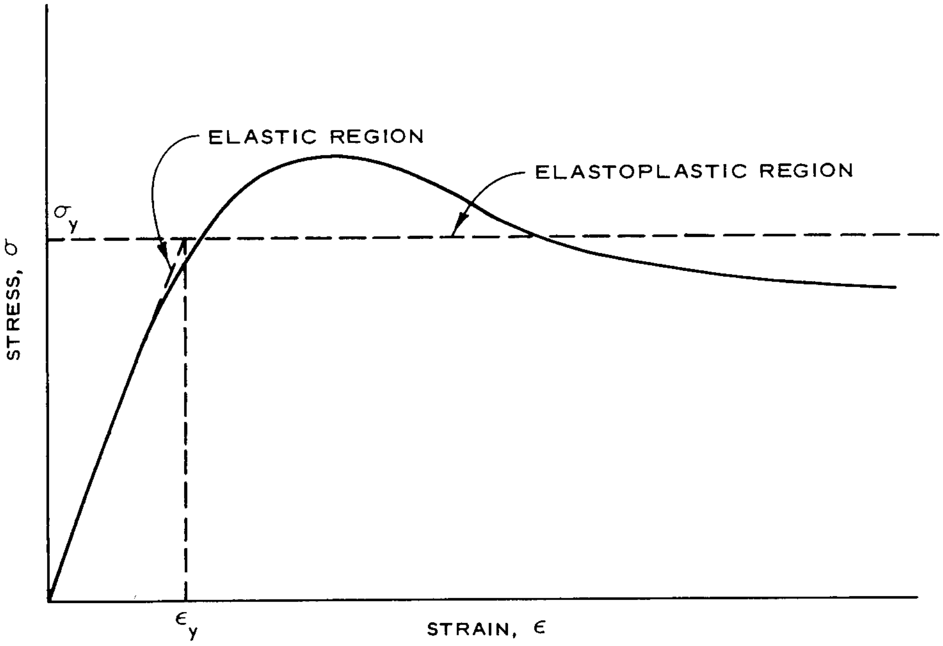


Figure 2.6 Estimated stress-strain diagram for rock.

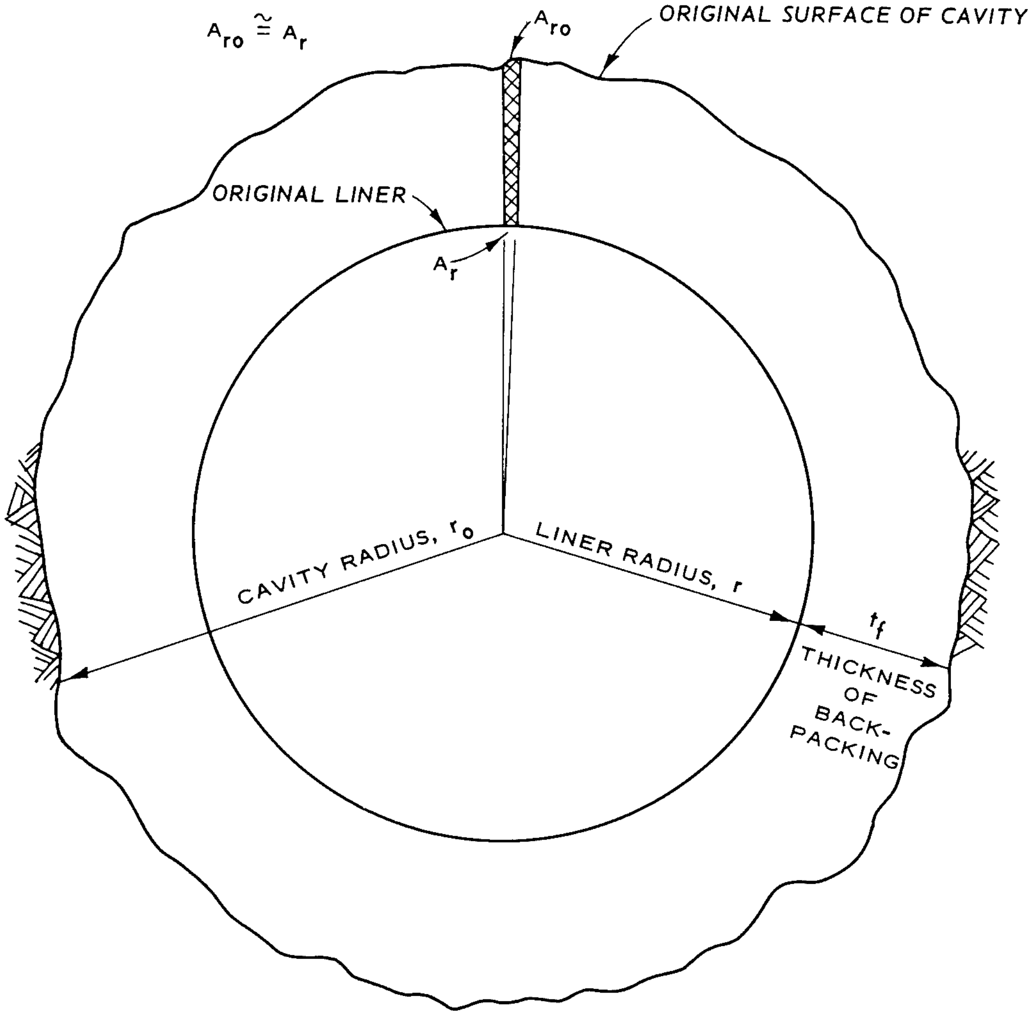


Figure 2.7 Cavity, liner, and backpacking.

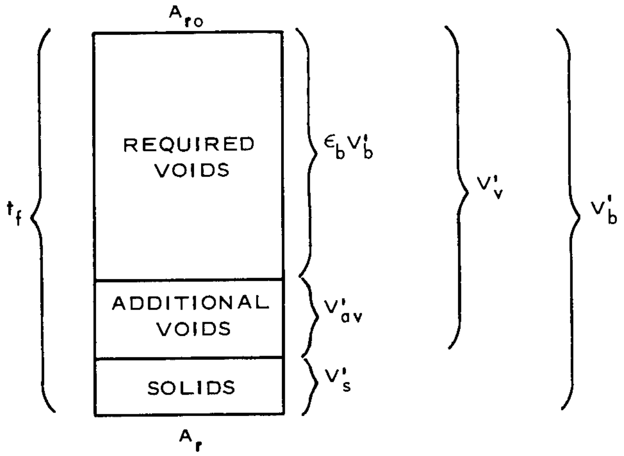


Figure 2.8 Diagram of the composition of a backpacking sample.

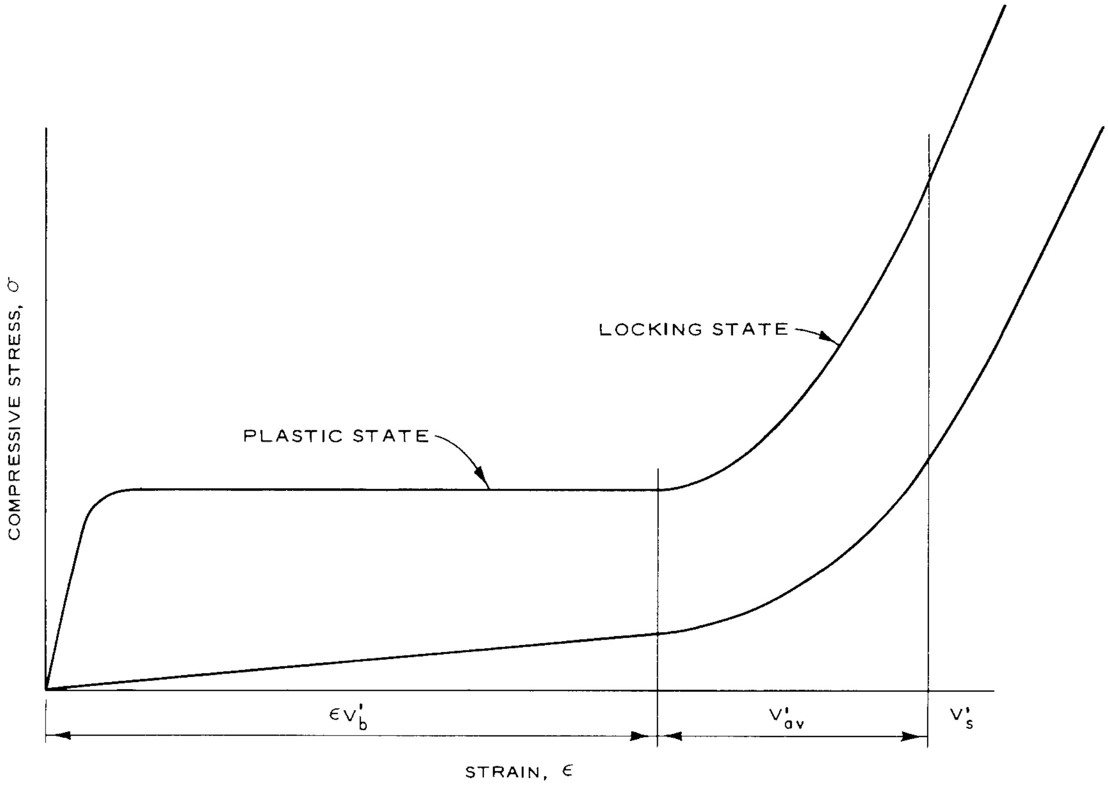


Figure 2.9 Distribution of backpacking voids and solids with respect to the stress-strain curve.

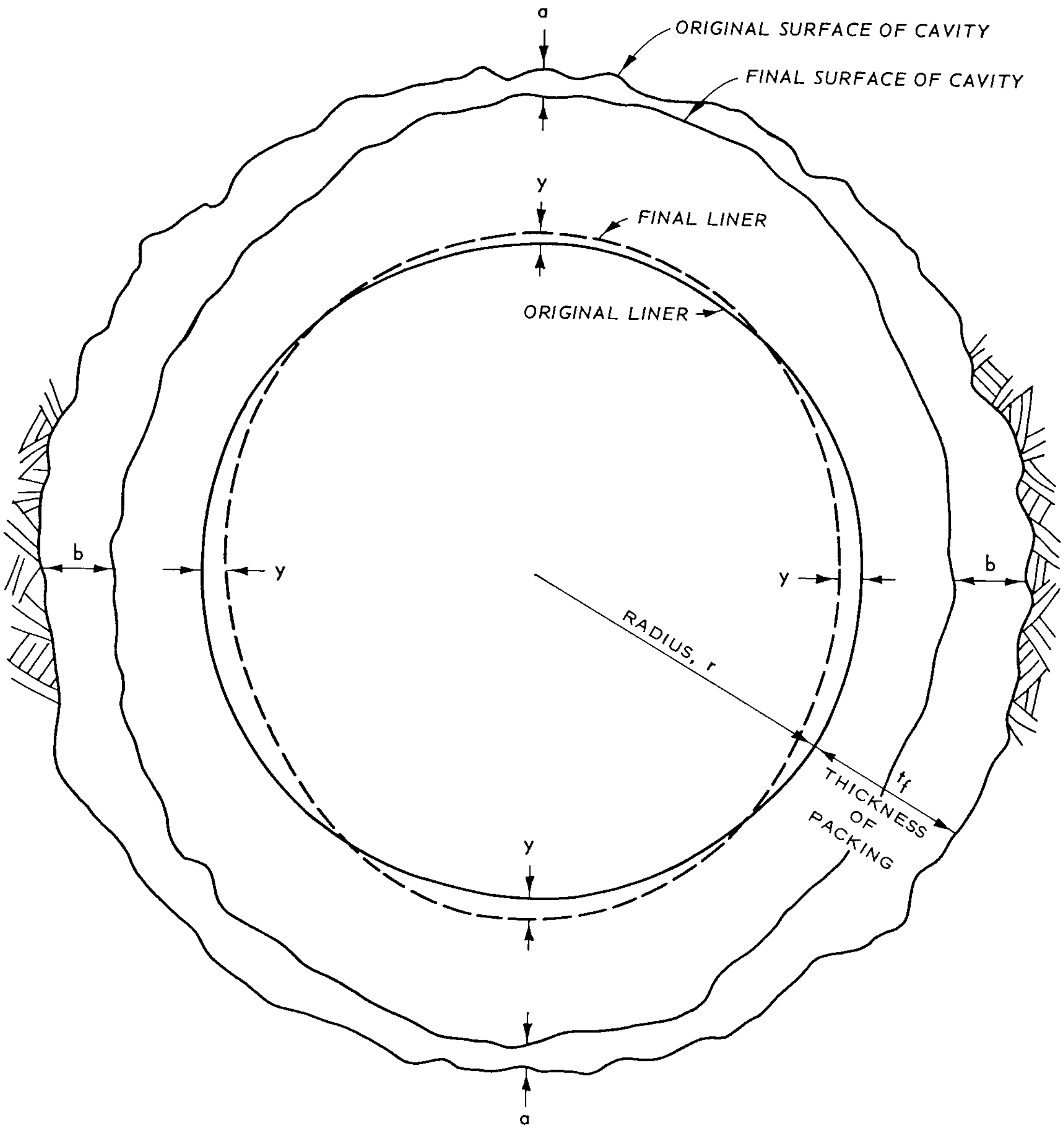


Figure 2.10 Deformation of liner and backpacking.

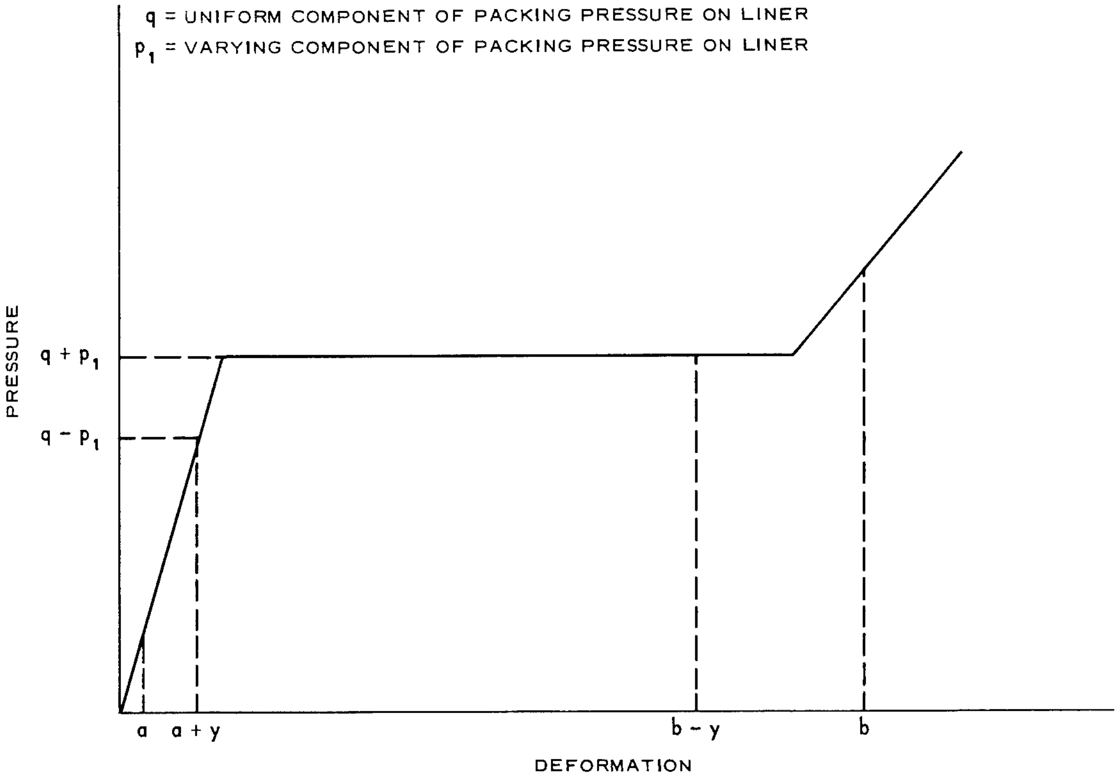


Figure 2.11 Ideal elastoplastic load-compression relation for backpacking.

CHAPTER 3

DESCRIPTION OF MATERIALS

3.1 GRANULAR MATERIALS

Low-density granular materials, when subjected to one-dimensional compression loading, generally yield a stress-strain relation that approximates the plastoelastic curve shape. This behavior, while not as ideal as an elastoplastic behavior, is still attractive from an economic viewpoint since granular materials are often considerably cheaper than the materials that can produce the ideal behavior.

Some naturally occurring materials (volcanic cinders) can often be put in the desired aggregate form by the simple application of a mechanical crushing and sieving process, while other naturally occurring materials (clay, shale, perlite, vermiculite) require the application of both a thermal expanding process and then the crushing and sieving process.

Because of their aggregate shape, low strength, and high deformability, many synthetic materials (phenolic microballoons, expanded polystyrene beads, ethylene-vinyl acetate copolymer beads) manufactured for purposes other than that of a backpacking aggregate can be pressed into service in that capacity. The waste or scrap from various industrial processes is often in an aggregate form (foamed aluminum scrap, expanded polystyrene plastic scrap, expanded polyvinylchloride scrap) and, depending on the properties of the original material, may be suitable for backpacking use.

The following paragraphs on granular materials do not encompass all of the types of materials that could be used as backpacking aggregate, but describe some typical varieties that are available in most areas.

3.1.1 Volcanic Cinders. Lightweight rocks of volcanic origin (scoria) occur in many parts of the world. Their lightweight structure was formed by escaping gases when the material was still in a molten state. The resulting rock is highly vesicular, coarsely cellular rock which is petrographically classified as the glassy equivalent of the mafic rocks.

The vesicular rock investigated in this program was a volcanic cinder (SM-35) obtained from a cinder cone about 150 miles north of Las Vegas, Nevada. The reddish-brown cinders were very friable and had an irregular and angular shape. The cinders had a bulk density of 47.9 pcf and following particle-size distribution:

Sieve Analysis	
Sieve Size	Cumulative Percent Passing
3/4 inch	100
1/2 inch	74
3/8 inch	42
No. 4	1

3.1.2 Expanded Perlite. Perlite aggregate is a naturally occurring siliceous rock which has been expanded to from 4 to 20 times its original volume by heating. Perlite rock is found throughout the Rocky Mountain area, but no two deposits produce expanded perlite with the same physical properties.

Expanded perlite aggregate from two different sources but with identical densities and gradations can produce two widely different aggregate crushing strengths (Reference 18). Before using perlite aggregate as a plastoelastic shock-absorbing material, it is advisable to thoroughly evaluate and control (1) the aggregate source, (2) methods of expanding, and (3) uniformity of the expanded material in order to achieve a satisfactory backpacking system.

The perlite aggregate (SM-22) investigated had an as-received bulk density of 10.2 pcf with the following particle-size distribution:

Sieve Analysis (As-Received)

Sieve Size	Percent Passing
No. 8	100.0
No. 16	57.0
No. 30	27.4
No. 50	12.2
No. 100	4.0

3.1.3 Expanded Vermiculite. Vermiculite is a hydrated magnesium-aluminum-iron silicate that is thermally exfoliated in special furnaces to form a lightweight expanded aggregate of the same name. The expanded vermiculite marketed in this country is available in four gradations and is generally obtained from two major domestic sources in Libby, Montana, and Travelers' Rest, South Carolina. The aggregate used in this study was vermiculite standard-grade No. 3 (SM-25) and had a bulk density (as-received) of 8.0 pcf and a gradation as shown below. It is normally used for plastering and insulating concrete operations.

Sieve Analysis (As-Received)

Sieve No.	Size Opening	Cumulative Percent Passing
	inches	
4	0.187	100.0
8	0.0937	95.8
16	0.0469	49.7

(Continued)

Sieve Analysis (As-Received)

Sieve No.	Size Opening	Cumulative Percent Passing
	inches	
30	0.0232	15.2
50	0.0117	7.6
100	0.0059	3.4
200	0.0029	1.5

3.1.4 Expanded Shale. When certain clays and shales are heated in rotary kilns or sintering hearths to a semiplastic stage often referred to as "the point of incipient vitrification," they expand to as much as seven times their original volume due to the formation of gas within the material at the fusion temperature (Reference 19). The cellular structure is retained upon cooling, thus giving rise to a material with a desirable void content from the shock-dissipation viewpoint.

The expanded shale (SM-2) used in these tests was obtained from a local supplier and had a bulk density of 49.5 pcf with the following gradation:

Sieve Analysis (As-Received)

Sieve Size	Percent Passing
1/2 inch	100
3/8 inch	85
No. 4	33
No. 8	15
No. 16	4
No. 30	2
No. 50	1

3.1.5 Expanded Clay. A lightweight aggregate made from expanded clay (SM-1) was obtained locally in a gap-graded condition. The material was evaluated in this condition because the gap grading would provide additional voids in any large volume of the aggregate, thus allowing more consolidation of the volume when loaded. The aggregate received was both of the normal lightweight structural concrete variety and also a variety of the same type of material which had been left in the expanding kiln too long and had become overburned. This overburning resulted in a frangible material that is somewhat weaker at comparable strains when compared with the normally expanded aggregate.

Three gradations of each variety were evaluated in this study, and the as-received properties are shown in Table 3.1.

3.1.6 Phenolic Microballoons. Syntactic foams are made with conventional polyester or epoxy resins as the binder and prefabricated microscopic hollow spheres as a filler. These hollow spheres or microballoons are made from phenolic resin and are filled with an inert gas, primarily nitrogen.

Phenolic microballoons (SM-20) with a bulk density of 8.3 pcf and the following particle-size distribution were evaluated for this study:

Sieve Analysis

Sieve Size	Percent Passing
No. 50	100.0
No. 100	91.3
No. 200	30.2
No. 325	7.5

Hollow glass microspheres resembling the phenolic microballoons in particle-size distribution and bulk density are also commercially available.

3.1.7 Expanded Polystyrene Beads. The usual practice in manufacturing polystyrene beads is to polymerize styrene, which contains a blowing agent (C_5 to C_7 saturated hydrocarbons) in an aqueous emulsion. The resulting products are granules or beads of unexpanded polystyrene. The application of one of a number of thermal processes to the unexpanded beads causes the volatilization of the blowing agent present in the unexpanded granules, thus causing expansion into a bead form. The type of thermal process used and its control determine the final density of the expanded bead. The polystyrene beads (SM-21) used as aggregates in this program were expanded commercially using an infrared heating system; resulting expanded density was 2 pcf. A typical analysis of the unexpanded beads is as follows:

Typical Analysis of Unexpanded Polystyrene[a]	
Bulk density, pcf	38
Real density, pcf	65.6
Moisture, pct	0.05 to 0.10
Monomer content, pct	0.1 to 0.2
Relative viscosity (1 pct in toluene)	2.0 to 2.1
Volatile content, pct	5.0 to 6.0
Blowing agent	n-pentane or isopentane

[a] Furnished by the manufacturer.

The expanded beads utilized in this program were both white and colored, nonself-extinguishing pellets with the following physical properties:

Actual Analysis of Expanded Polystyrene	
Bulk density, pcf	1.98
Bead colors	White and blue
Standard sieves:	

Sieve No.	Size Opening	Cumulative Percent Passing
	inches	
4	0.187	100.0
8	0.0937	17.5
16	0.0469	0.0

3.1.8 Ethylene-Vinyl Acetate Copolymer Beads. By polymerizing certain chemical compounds to form copolymers, thermoplastic resins with properties similar to rubber or plasticized polyvinylchloride resins can be developed and designed to have many combinations of physical characteristics advantageous to shock-isolation techniques. The resin used in this investigation was ethylene-vinyl acetate copolymer (SM-29(1) and (2)) and was obtained in an almost uniform bead form with 98 percent of the beads being retained on a No. 8 sieve. SM-29(1) had a bulk density of 35.9 pcf, and SM-29(2) a bulk density of 37.1 pcf.

3.1.9 Foamed Aluminum. The development and application of foamed plastics as a construction material have prompted the development of similar metal base materials (Reference 20). Careful design of cellular metals to utilize the full potential of the characteristics of the base material has resulted in a number of foamed metals that satisfy a wide variety of needs, one of which is energy absorption (Reference 21). Normally occurring industrial waste from a foamed metal process or the deliberate manufacture of foamed metal in an aggregate form provides two more sources of materials that could be satisfactorily used as backpacking.

The material investigated in this study was a deliberately manufactured foamed aluminum aggregate (SM-3) with a bulk density of 9.0 pcf and the following particle-size distribution:

Sieve Analysis (As-Received)	
Sieve Size	Percent Passing
3/4 inch	100.0
1/2 inch	84.6
3/8 inch	10.3
No. 4	0.0

3.1.10 Expanded Polystyrene Plastic Scrap. The waste products resulting from manufacture of foamed plastics can also be utilized as a granular-type backpacking material. Two different expanded polystyrene plastic waste aggregates were investigated for this study. Type A was deliberately manufactured from the material (SM-4) described in Section 3.3.3 by pulverizing the material in a hammer mill. The resulting aggregate form had the following particle-size distribution and a bulk density of 0.81 pcf:

Sieve Analysis	
Sieve Size	Percent Passing
3/8 inch	100
No. 4	61
No. 8	20
No. 16	10
No. 30	5

The other expanded polystyrene plastic waste aggregate, Type B (SM-6), is the result of an actual manufacturing process and had the following particle-size distribution and a bulk density of 1.06 pcf:

Sieve Analysis	
Sieve Size	Percent Passing
3/8 inch	100
No. 4	80
No. 8	44
No. 16	8
No. 30	2

3.1.11 Expanded Polyvinylchloride Plastic Scrap. The expanded polyvinylchloride plastic waste (SM-8) in the granular or aggregate form used in this study was the result of a manufacturing process that utilized the same type of material described in Section 3.2.1. This waste material had a bulk density of 0.35 pcf and the following particle-size distribution.

Sieve Analysis	
Sieve Size	Percent Passing
1/2 inch	100
3/8 inch	72
No. 4	13
No. 8	3
No. 16	1

3.2 FLEXIBLE FOAMED PLASTICS

A foamed plastic is an expanded, spongy resinous material having a distinctly cellular structure which may be either open- or closed-cell. Most liquid resins or plastic melts can be made into a foamed form by introducing a gaseous blowing agent at an opportune time in the process, and then freezing or setting the expanded mass by cooling or curing (Reference 22).

Flexible foamed plastics subjected to compressive loads exhibit non-Hookean behavior and begin deforming plastically under the slightest increases in loading, thus resembling the plastoelastic behavior described earlier. Vinyl copolymers, silicone, and linear polyurethane plastic resins are most commonly used in the production of the flexible group of foams (Reference 23).

3.2.1 Vinyl Foams. The most common vinyl foam is the open-cell or flexible foam made from vinyl chloride copolymers. It is made by incorporating a chemical blowing agent or dispersing an inert gas under pressure into a liquid plastisol mixture of the vinyl resin and plasticizer. The resultant mixture is then preheated to cause an expansion of the gas that forms a frothy semiliquid gel which is cured at higher temperatures to a flexible spongy solid. Closed-cell vinyl foams can also be made by pressure-blowing with an inert gas and curing under pressure in closed molds, thus restricting the size of the finished foam to the size of the mold (Reference 23).

The flexible vinyl foams are commercially available in a wide range of densities; however, the average strength range does not vary appreciably. In a density range from 4 to 12 pcf, the average compressive strength at 25 percent deformation will vary from 0.1 to 10 psi.

The material investigated in this study was a flexible, expanded, modified polyvinylchloride closed-cell material (SM-9) with a density of 3.0 pcf.

3.2.2 Silicone Foams. There are three basic types of silicone foams: premixed powders, room-temperature-curing foams, and silicone rubber foams (References 22 and 23).

Silicone foaming powders are expanded by means of a blowing agent which decomposes into nitrogen gas and an alkaline by-product at about 300 F. The silicone resins used are solventless polysiloxanes with a melting point of 120 to 140 F. In the presence of an appropriate catalyst, they become thermoset through the condensation of hydroxyl groups. To make a foam, the powder is simply heated above 300 F. Expansion and gelation are synchronized, and the resin gels when maximum expansion is attained.

The room-temperature-curing type is based upon chemical reaction between two silicone components in the presence of a catalyst. The reaction is slightly exothermic, but temperatures seldom exceed 150 F even in very large pours. Hydrogen gas is liberated as the expanding agent. The expansion factor is in the range of seven to ten times.

The production of a silicone rubber foam is very similar to that of the room-temperature-curing foams in that they are made by mixing two components. The expansion is instantaneous with the material developing 80 percent of its ultimate strength within five minutes after blending has begun. By varying formulation and foaming techniques, it is possible to produce either open- or closed-cell foams.

No silicone foams were tested in this program. A stress-strain curve for a silicone foam can be found in Reference 24.

3.2.3 Flexible Polyurethane Foams. Flexible polyurethane foams are produced by polymerizing a di-isocyanate and a polyether or polyester resin in the presence of a blowing agent. The di-isocyanate reacts with the resin, converting it to a high-molecular-weight elastomer, and at the same time reacts with any water present to generate carbon dioxide which foams the plastic. Fluorocarbons are sometimes used as auxiliary blowing agents. Catalysts and surfactants (primarily silicone) are also needed to control the rate of foaming and the cell structure (Reference 23). The commercially available, predominantly open-cell, flexible polyurethanes have a density range from 1 to 6 pcf, with average compressive stresses less than 10 psi.

Two flexible polyurethane samples were investigated. The first sample (SM-55) had a bulk density of 1.4 pcf, the second (SM-57) a bulk density of 4.0 pcf.

3.3 RIGID FOAMED PLASTICS

Rigid foamed plastics subjected to compressive loads approach Hooke's law in behavior, i.e. stress is linearly proportional to strain until the crushing strength of the material is reached. The material then behaves like a viscous liquid. This behavior duplicates the elastoplastic behavior described earlier. The epoxy, phenolic, cellulose acetate polystyrene, and polyurethane plastic resins are most commonly used for the production of rigid foams (Reference 22).

3.3.1 Epoxy Foams. A typical formulation for a rigid epoxy foam contains a liquid epoxy resin, a wetting agent, a solid heat labile compound, and an aliphatic polyamine curing agent. When this formulation is heated to approximately 212 F, the heat labile compound decomposes and, depending on the formulation, provides either carbon dioxide or nitrogen gas which expands the resin into a closed-cell foam. The aggregate heat of the resin, which should be maintained for 15 minutes after foaming begins, and the heat of the exothermic reaction should accomplish the curing (Reference 22).

This is a free-rise foam with volume expansion limited only by the thermodynamics and reaction rate of the system. The resulting foams have densities from 5 to 13 pcf and compressive strengths from 100 to 450 psi. A new technique currently under development utilizes chlorofluorocarbon as a blowing agent in the foaming process and results in densities from 2 to 3 pcf with strengths reduced to 10 to 30 psi. Epoxy foams can be either poured in place or utilized in a spray-type application.

The epoxy foam (SM-18) evaluated in this study had a density of 5 pcf.

3.3.2 Phenolic Foams. There are two basic types of phenolic foams commercially available: (1) reaction type and (2) premixed cellular mortar or syntactic foam (see Section 3.1.6). Since the syntactic foams normally produce compressive strengths well in excess of the upper stress limit of this investigation, the discussion is limited only to the reaction-type foam.

The reaction-type phenolic foams are made from a thermosetting liquid phenolic resin mixed with an acid catalyst just prior to use. The catalyst causes a rapid exothermic reaction which vaporizes some of the volatiles and causes the resin to expand. The entire expansion process to a volume as much as 200 times the original liquid resin volume may take less than 1 minute (Reference 23).

Densities varying from 0.33 to 25 pcf can be produced using poured-in-place techniques with compressive strengths ranging from 2 to 1,500 psi for that density range. The phenolic foam (SM-36) used in this study had a density of 15 pcf.

3.3.3 Cellulose Acetate Foams. Expanded cellulose acetate is produced by a continuous extrusion process wherein the molten plastic resin is converted to a semirigid foam by a flash vaporization of a volatile solvent (Reference 22). Since it is an extruded product, it cannot be foamed in place and is presently available in limited shapes and sizes. The density ranges from 4 to 8 pcf with average compressive strengths of up to 150 psi. The material is easily pieced together by simple gluing to form any desired configuration.

The material used in this study was a closed-cell, expanded cellulose acetate (SM-61) with a density of 6.4 pcf.

3.3.4 Polystyrene Foams. Polystyrene foams are of two types: (1) an expanded foam produced by dispersion of a gas in the melted plastic resin, and (2) the expandable polystyrene resin which contains a blowing agent and upon heating will expand into a unicellular structure or individually expanded beads or pellets (see Section 3.1.7) if suspended in a suitable medium (Reference 25).

The polystyrene foams in either form are generally available in a density range from 1 to 6 pcf with a respective compressive strength range from 10 to 300 psi. The closed cells, controllable density, and low water absorption make this a desirable material even though at present it cannot be poured in place but has to be prefabricated.

Both types of polystyrene foam were investigated during this study. Type A (SM-33) was the homogeneous type with a density of 1.6 pcf; Type B (SM-4) was composed of molded and fused expanded polystyrene beads and had a density of 1.0 pcf.

3.3.5 Rigid Urethane Foam. Rigid urethane foams are made by two processes: (1) the quasi prepolymer method and (2) the one-shot method. In the first process, the di-isocyanate is reacted with a portion of the polyether to give an NCO-terminated prepolymer. The prepolymer is then reacted with the rest of the polyether, catalyst, surfactant, and fluorocarbon to produce the foaming action. In the second process, no prereaction step is required. Each component can enter the mixing head separately or all components except the di-isocyanate can be premixed. In this process a modified di-isocyanate providing increased functionality must be used (Reference 25).

Rigid polyurethane foams are available in a wide range of densities and strengths, but for the level of interest of this study they can be restricted to a density range from 1.5 to 18 pcf with respective compressive strengths from 15 to 1,100 psi. The foam has a low controllable density, excellent dimensional stability, low water absorption, and can be poured in place.

Two different rigid polyurethane foams were investigated for this study. Type A (SM-19) is normally used as an expansion joint filler and had a density of 1.9 pcf; Type B (SM-34) was prefabricated for use as backpacking on Operation NOUGAT, Shot HARD HAT (Reference 26), and had a density of 6.2 pcf.

3.4 FOAMED RUBBER

Foamed rubbers are available in two principal types. The basic or original type is a sponge rubber variety that is made by subjecting a rubber polymer to the action of a blowing agent, primarily nitrogen. These polymers can be either gas blown or chemically blown. In the first case, the blowing gas is mechanically forced into the polymer melt; in the second case, a chemical that contains the blowing agent is introduced into the melt and under the combined action of heat and pressure releases the blowing gas into the melt. In either case, foamed rubber can be closed-cell or open-cell. When a closed-cell rubber is desired, the expansion process is regulated so that the blowing gas does not explode the rubber cells that contain it. In open-cell rubber, the gas is allowed to explode the cells, thus resulting in an interconnected cell system.

The second type of foamed rubber is a by-product of the first type. The waste material from the fabrication processes applied to the gas-blown rubber is retrieved and chopped into small pieces. An adhesive is then added to the pieces, and the entire mass is subjected to a heat and pressure treatment. The resulting product is a bonded mass of foamed rubber. The waste material used in this process is derived predominantly from the closed-cell gas-blown rubber. It is not uncommon to mix various foamed polymers together to form a single variety of bonded foam rubber.

Only the bonded foam rubber (SM-31(B) and (C)) was investigated for this program. SM-31(B) had a bulk density of 26.0 pcf, and SM-31(C) a bulk density of 40.4 pcf.

3.5 CELLULAR METALS

Cellular metal is generally produced by a foundry process. Prepared molds are packed with a suitable grade of soluble granules in the most effective manner permitted by the particle shape. All of the particles touch many adjoining particles. The entire mold and the granules are preheated. Molten metal is then poured over the granules and by use of various techniques is forced into all available voids. The composite mass is allowed to solidify. After removal from the mold, the soluble granules are dissolved or leached away from the composite mass by various processes and only the cellular metal remains. By this process the size, geometry, and distribution of the voids or cells can be controlled (Reference 21).

Cellular metals can also be made by incorporating a material containing a blowing agent into the melt. The heat of the melt releases the blowing gas which can be trapped in the metal if the metal is cooled rapidly. Higher densities are usually obtained with this process than those achieved with the process discussed in the preceding paragraph.

Aluminum foams with two different sizes of mesh (SM-3) were evaluated during this study and will be referred to as coarse mesh and fine mesh with densities of 10 and 13 pcf, respectively. The foamed aluminum aggregate described in Section 3.1.9 was manufactured from the coarse mesh variety. Because of size limitations on the material received, the samples evaluated for compressive strength were only 1-inch cubes.

3.6 CELLULAR GLASS

Cellular or foamed glass is composed of borosilicate-type glass processed by fusion to form a homogeneous rigid mass of hermetically sealed cells. The glass ingredients are melted at a temperature of approximately 2,900 F. The resulting glass is drawn off in solid form and then finely ground. During this crushing operation a very small amount of pure carbon is thoroughly mixed with the glass. This mixture is then reheated to approximately 1,700 F, during which period the cellulation takes place. The material evaluated for this study (SM-30) had a bulk density of 9.1 pcf.

3.7 HONEYCOMBS

3.7.1 Paper Honeycomb. Paper honeycomb is a kraft fiber cellular structure fabricated to form nested, hexagonal-shaped voids. It is available in a number of paper weights, cell sizes, and densities. The paper can be either untreated kraft or a phenolic or other plastic resin-impregnated paper. The treated kraft provides greater permanence and wet strength. Additional varieties that furnish quantities of urethane foam at the ends of the honeycomb cells are also available. These varieties provide stronger cells and a more watertight system. No paper honeycombs were tested in this program.

3.7.2 Metallic Honeycombs. Metallic honeycomb is a stable, naturally vented, rigid-core material which is made of cross-laminated corrugations of any one of several types of sheet metals. It is available in various foil thicknesses, corrugation heights, and laminations. Two aluminum honeycombs (SM-64) were evaluated. Type A had a foil thickness of 0.003 inch, a corrugation height of 3/16 inch, a bulk, unfaced density of 4.0 pcf, and was laminated at an angle of 45 degrees. Type B was identical with Type A except the corrugations were only 3/32 inch with a resulting bulk density of 8.3 pcf.

3.8 FOAMED SULFUR

Foamed sulfur normally is not commercially available but has been developed (References 27 and 28) for use as a shock-isolation material for deeply buried structures. The technique used in its production is simply the manner in which a plasticizer, stabilizer, and blowing agent are combined with a sulfur melt in order to produce a foam.

Specifically, foamed sulfur is made by melting sulfur and heating it to 180 C; then a styrene monomer is added, mixed, and allowed to react with the sulfur. While still at the same temperature, a polysulfide plasticizer is added and mixed. Talc, used as a mechanical stabilizer, is added next. The temperature is then reduced to 160 C and phosphorus pentasulfide, an additional stabilizer, and calcium carbonate, used as a part of the expansion process, are added. An acid is then added, and an immediate expansion process occurs as a result of the gas generated by the acid-carbonate reaction. The expanded mass is allowed to harden.

A sample evaluation of the foamed sulfur was made by the Southwest Research Institute, San Antonio, Texas. The testing technique varied from that used in this study in that the compressive strengths and deformations were determined by forcing a 1-inch penetrometer into a confined 2-inch cube. The two foamed sulfur formulations used to fabricate the samples (see curves in Figures 5.27 and 5.28) are as follows:

Formulation A:

Constituent	Percent
Sulfur	89.7
Phosphorus Pentasulfide	4.4
Talc	4.4
Calcium Carbonate	0.9
Phosphoric Acid	0.67

Formulation C:

Constituent	Percent
Sulfur	90.1
Phosphorus Pentasulfide	4.5
Talc	4.5
Sodium Bicarbonate	0.9

3.9 LOW-DENSITY CONCRETES

Low-density concrete, as used in this report, is defined as concrete made with or without aggregate additions to portland cement, water, and air to form a hardened material that will have a unit weight of 50 pcf or less when oven-dried. Low-density concrete is normally available in two forms: (1) the lightweight aggregate type, which is made predominantly with low-density mineral aggregates, and (2) the cellular type, which is made by forming a cement matrix around air voids that are generated by preformed foams or special foaming agents with or without the addition of mineral aggregate. Both types of low-density concretes were evaluated in this study.

3.9.1 Low-Density Aggregate Type. The lightweight aggregate type, which normally utilizes mineral aggregates, was modified to include two low-density, synthetic aggregates: expanded polystyrene beads (Section 3.1.7) and deliberately manufactured expanded and molded polystyrene scrap (Section 3.1.10). The mineral aggregate used was expanded vermiculite (Section 3.1.3). The mixture using the deliberately manufactured scrap polystyrene also included a cement-replacement material, friant pumicite (AD-6(4)). The replacement material:cement ratio was 2.33 by weight.

In all, three different low-density aggregate-type concretes were evaluated. They were proportioned on the basis of a cement:aggregate ratio (cubic foot of loose cement per cubic foot of loose aggregate) and a water:aggregate ratio (gallons of water per cubic foot of loose aggregate). The actual mixture proportions used to fabricate the concretes (see Figure 5.29 for test results) are as follows:

	Vermiculite Concrete	Expanded Polystyrene Bead Concrete	Manufactured Polystyrene Scrap Concrete
Cement:aggregate ratio	0.127	0.128	0.124
Water:aggregate ratio	3.5	1.8	4.6
Replacement material:cement ratio	--	--	2.33
Unit weight, pcf	47.6	36.0	35.3
Slump, inches	8	10	11
Air content, percent	42	29	25

3.9.2 Low-Density Cellular Type. The cellular type of low-density concrete used in this investigation was made by mechanically blending a preformed foam into a suitable slurry and allowing the slurry to harden around the air bubbles in the foam.

Two varieties of cellular concrete were prepared and evaluated: (1) two mixture designs of the neat cement variety that used only Type III cement (RC-519) and water to form the slurry, and (2) a cement-filler material variety that had a mineral filler added to the cement normally used. The actual mixture proportions used to obtain the concretes evaluated are as follows:

WES Mix No.	Water: Cement Ratio	Filler: Cement Ratio	Unit Weight	Air Content	Cement Content	Filler Content	Water Content
			pcf	pct	bags/yd^3	bags/yd^3	gal/yd^3
64	0.97	1.0	40.6	63.5	3.93	3.69	43.0
128	0.93	--	41.0	57.5	6.10	--	64.0
130	0.96	--	35.0	63.3	5.12	--	55.7

1. Admixtures. To facilitate handling and increase workability, the low-density aggregate-type concretes required the use of an air-entraining admixture. The admixture used was laboratory stock AEA-535, neutralized vinsol resin solution.

2. Foaming Agents. A foaming agent, AD-186, was used to provide the stable air-bubble system necessary for the fabrication of the cellular concretes. A spectroscopic analysis of the foaming agent indicated the presence of decomposition products of proteins reacted with aliphatic fatty acids or salts of diaphatic fatty acids.

The foaming agent is marketed as a hydrolyzed, stabilized protein foaming agent.

3. Cement. Type III portland cement (RC-519) was used for all six mixtures designs and had the following chemical and physical characteristics:

Chemical Analysis		Physical Properties	
Constituents	Percent		
SiO_2	19.9	Normal consistency	27.2
Al_2O_3	5.5	Setting time, Gillmore, hours:minutes	
Fe_2O_3	4.6	Initial	2:25
CaO	63.2	Final	5:25
MgO	1.8	Autoclave expansion, pct	0.01
SO_3	2.6		
Ignition loss	1.6	Air content of mortar, pct	7.2
Total	99.2	Compressive strength of mortar, psi	
Insoluble residue	0.12	1 day	2,175
Na_2O	0.13	3 days	3,808
K_2O	0.26	7 days	5,164
Total alkalies as Na_2O	0.30	Surface area, Blaine fineness, cm^2/g	4,305
		Specific gravity	3.13
C_3A	7		

(Continued)

Chemical Analysis		Physical Properties	
Constituents	Percent		
C_3S	55	Heat of hydration, cal/g	
C_2S	16	7 days	81.6
C_4AF	14	28 days	91.7
$CaSO_4$	4		

4. Mineral Filler. The mineral filler used in the cement-replacement type of cellular concrete was a finely powdered silica flour which had 100 percent passing a No. 200 sieve and a specific gravity of 2.66.

5. Cement-Replacement Materials. Friant pumicite is a finely divided pozzolanic material which can be used as a substitute for a portion of the portland cement in concrete. The pumicite used as a replacement material in the polystyrene scrap aggregate mixture was AD-6(4) and had a specific gravity of 2.36 with 98.4 percent passing a No. 325 sieve.

TABLE 3.1 PROPERTIES OF AS-RECEIVED, EXPANDED, LIGHTWEIGHT CLAY AGGREGATE

	Normal Aggregate			Overburned Aggregate		
Gradation	3/4 to 1/2 in.	1/2 to 3/8 in.	3/8 in. to No. 4	3/4 to 1/2 in.	1/2 to 3/8 in.	3/8 in. to No. 4
Bulk Density, pcf	42.9	44.3	48.2	28.8	29.7	29.2
Specific Gravity	1.52	1.53	1.61	1.12	1.14	1.18
Absorption, pct	17.7	21.7	19.7	21.6	21.1	25.4

CHAPTER 4

TEST EQUIPMENT AND PROCEDURES

4.1 TEST EQUIPMENT

To provide adequate lateral restraint to the materials that would be tested in one-dimensional compression, a specially designed confining chamber was fabricated from a solid core of stainless steel. The chamber has a 6-inch inside diameter with 1-inch-thick chamber walls and is seated in and bolted to a baseplate of the same material. The large wall thickness resulted in negligible lateral strain for the largest vertical loads contemplated for the proposed tests. The confining chamber can accommodate materials up to 7 inches in height; however, for this program only 6-inch-high samples were tested in the chamber.

Loads were applied to all samples by means of a 30,000-pound Universal testing machine operating at a constant straining rate of 3 percent strain per minute for all samples tested. The load was transmitted from the testing machine to the sample by means of a nominal 6-inch-diameter loading piston for all 6-inch-diameter and 6-inch-square samples. A standard 3-inch-diameter loading head was utilized on all 1- and 2-inch cube samples. The testing configuration for a 6-inch-diameter fully confined sample is shown in Figure 4.1.

4.2 TEST PROCEDURES

4.2.1 Granular Materials. All granular materials were tested at their as-received bulk densities. The confining chamber was filled in three equal layers, and the chamber was lightly tapped with a rubber mallet after each layer was placed. It was found that this procedure enabled the as-received bulk density to be duplicated in the confining chamber. The materials were placed to a total sample height of 6 inches.

The load was applied to the granular samples by means of a nominal 6-inch-diameter loading piston traveling at a constant rate of 0.18 in./min (3 percent strain per minute). Where practical, all samples were loaded to a final stress of 1,000 psi.

Prior to the one-dimensional compression test, sieve analysis of each material was made in accordance with The Corps of Engineers Handbook for Concrete and Cement Test Method CRD-C 103-60, "Method of Test for Sieve Analysis of Fine and Coarse Aggregates for Use in Portland-Cement Concrete." A similar analysis was made of the crushed expanded clay aggregate resulting from the one-dimensional compression test.

4.2.2. Foamed or Distended Materials. All foamed or distended materials not in a granular form, with the exception of the honeycombs, foamed sulfur, and low-density concretes, were prepared and tested in accordance with ASTM Specification D-1621-64 Standard

Method of Test for Compressive Strength of Rigid Cellular Plastics, with the following modifications:

1. All materials were allowed to deform, if practical, until a total load of 1,000 psi had been placed on the material.

2. All materials were deformed at a constant straining rate of 3 percent of the initial height of the sample per minute.

The materials tested were in a cube form and had a height of 2 inches with the exception of the foamed aluminum, which was available only in 1-inch pieces.

4.2.3. Paper Honeycombs. Curves for paper honeycombs are presented in Figure 5.25 (Reference 29). Honeycomb pads 16-1/2 inches by 17-1/2 inches with thicknesses of 1 inch and 4 inches were tested statically. The 1-inch-thick pads were deformed at a rate of 0.62 in./min; the 4-inch pads were deformed at rates of from 0.08 to 0.10 in./min.

4.2.4 Metallic Honeycombs. The metallic honeycombs were tested using the same procedures described in Section 4.2.2 for foamed or distended materials with the exception that all specimens were 6-inches square by 2-inches thick. A 6-inch-square steel plate covered the surface to be loaded on each sample. The load was transferred from the testing machine to the steel plate by means of the nominal 6-inch-diameter loading piston. Samples were loaded at a straining rate of 3 percent strain per minute (0.06 in./min) until 80 percent total strain had occurred.

4.2.5 Foamed Sulfur. The sample evaluation of the foamed sulfur was made by the Southwest Research Institute, San Antonio, Texas. The testing technique varied from that used in this study in that the compressive strengths and deformations were determined by forcing a 1-inch penetrometer into a confined 2-inch cube. The cubes were sawed from larger pieces of foamed sulfur.

4.2.6 Low-Density Concretes. Because of the brittle nature of the low-density concretes, lateral restraint is necessary to eliminate spalling and crumbling of the material after its elastic yield point is reached. The concept of lateral restraint also approximates the condition of the material in a prototype situation. The restraint was provided by the same confining chamber used to evaluate the granular materials.

The samples tested were sawed from cast 6-inch-diameter by 12-inch-high cylinders with each cylinder yielding two nominal 6-inch samples. The original cylinders were cast and allowed to cure in the mold for 24 hours, after which they were removed and placed in polyethylene bags. The bags were sealed and placed in an ambient temperature of 73 ± 2 F for 13 additional days, at which time the cylinders were removed, sawed, and tested.

Loads were applied to the 6-inch-diameter by 6-inch-high concrete samples by means of a nominal 6-inch-diameter loading piston traveling at a straining rate of 0.18 in./min (3 percent strain per minute).

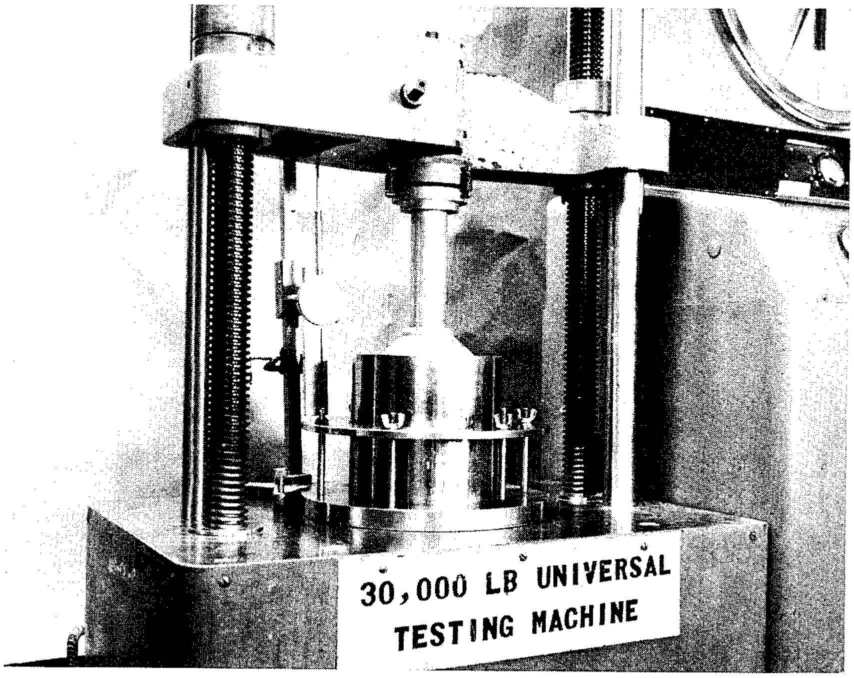


Figure 4.1 Testing equipment.

CHAPTER 5

DISCUSSION OF RESULTS

5.1 GRANULAR MATERIALS

As shown in Figures 5.2 to 5.12, granular materials of the varieties investigated in this study generally exhibit a plasto-elastic behavior. These materials are only typical samples of a large population of granular materials that exhibit that same behavior under the same loading conditions. The general stress-strain relation in granular materials is very complicated, however, and is to a large extent dependent on the type of material and the magnitude of the applied pressure. Reference 30 provides a description of a typical stress-strain curve and consequently the energy-absorbing mechanisms for granular materials which, although concerned with materials subjected to much higher stress levels, illustrate the phenomena necessary for backpacking using granular materials (Figure 5.1).

The behavior in Region 1, the very low-stress range, reflects rearrangement of the particles. When vesiculated granular particles are subjected to the same low stresses, fragmentation by shearing and crushing also occurs during the particle rearrangement, thus resulting in a concave upward curve for the same region (Reference 31).

The absorbed energy in both cases is usually nonrecoverable.

As the stress increases (Region 2), the particles begin to lock together in a stable matrix of elastic particles. Some rearrangement is still taking place; but the overall behavior is essentially nonlinear elastic in nature, therefore allowing most of the energy absorbed to be recoverable.

In Region 3, the stress magnitude is such that the particles begin to crush and further rearrange themselves. Most of the energy dissipated here in forming new surface and consolidating the particle is nonrecoverable.

Region 4 behavior is similar to that of Region 2 with some additional crushing taking place.

The average stress required for compaction depends on many factors, including the initial void ratio of the granular mass, the angularity of the particles, the duration and magnitude of the loading, and the inherent strength of the mineral or material which composes the grain (Reference 31). As the interest in granular materials for backpacking is at low stress levels and large strains, Region 1 and perhaps the lower portions of Region 2 as shown for the curves in Figure 5.1 are the regions of primary interest.

The stress-strain relation for granular materials does not produce the flat crushing-stress plateau necessary for transferring a constant stress to the liner. This is not desirable as it is relatively impossible for a liner interacting with the progressively increasing stress-strain relation of a plastoelastic material to develop a resistance characterized by a nearly uniform compression on all sides. Some granular materials, however, do yield a gradually increasing stress plateau (Figures 5.5, 5.6, 5.8, and 5.10) that does not produce large stress increases for small increases in deformation until very large total deformations have already occurred. As will be shown later, these materials may have an economic advantage over materials that possess an elastoplastic stress-strain relation and therefore might be considered for use as backpacking when cost is a governing factor.

Normally the strength of the grains of competent naturally occurring material is too great to provide the large deformations required before high applied pressures are reached. Some naturally occurring grains, however, do possess this deformation capability because of the very friable, vesicular nature of their grain. Volcanic cinders (Figure 5.2) are one such material and require only mechanical processing before they can be used. Other naturally occurring materials such as clay, shale, coal, vermiculite, and perlite can be altered by various mechanical and thermal methods (Reference 19) to produce grains of a composition suitable for backpacking purposes. The stress-strain relations for a few samples of an expanded clay, shale, vermiculite, and perlite are shown in Figures 5.3, 5.4, 5.5, and 5.6, respectively.

Often the expanded variety of a naturally occurring material can be tailored to meet certain strength or deformation requirements by varying the duration of the expanding process. In so doing, the strength of the final product will be varied and in turn will affect the deformations, as the amount of crushing that occurs depends on the strength of the grain. Figure 5.13 shows the effect of overburning a normal lightweight expanded clay aggregate. The overburning appears to reduce the amount of competent material in the aggregate, increase its void ratio, and slightly increase its porosity. By comparing the particle-size distribution for a particular gradation of both aggregate varieties after crushing to 1,000 psi, it can be seen (Figure 5.14) that the frangible, overburned material resulted in more fines than the normal aggregate which contributes considerably to the maximum consolidation of a given volume of aggregate.

Artificial grains can also be used for backpacking purposes. Industrial waste as well as artificial grains manufactured in the form of chips or aggregate often exhibits plastoelastic behavior in one-dimensional compression (Figures 5.7 to 5.12). The curves shown in Figures 5.7, 5.8, and 5.9 represent the behavior of grain-size materials that were produced for use in various industrial processes.

Numerous other varieties of both solid and hollow grain materials that exhibit the plastoelastic behavior are also commercially available.

Figures 5.10, 5.11, and 5.12 depict the behavior of a few varieties of industrial waste products. The foamed aluminum aggregate, although manufactured in the laboratory from the parent material, is representative of what might be expected from an industrial processing method. The two varieties of expanded plastic waste (Figures 5.11 and 5.12) are the result of actual industrial processing. Many waste materials might prove to be adequate, but because waste is only a by-product and is not deliberately manufactured, availability at the time and place the material might be needed could be a limiting feature.

The amount of moisture the foamed or expanded aggregates may absorb should also be considered when selecting a granular material for backpacking. If the voids in the aggregate can become filled with liquid, their effectiveness in absorbing energy and providing large deformations is greatly reduced. Most expanded varieties of the naturally occurring materials will absorb water in varying degrees depending on the material. Attempts to coat the natural grains with waterproofing materials have been partially successful. The artificial grains, however, absorb very little water, if any, compared with the naturally occurring expanded grains. The amount of moisture absorbed by the waste aggregates will depend, of course, on the composition of the parent material.

All of the grains discussed above could be incorporated into various types of binders or matrices. Upon hardening, the matrix could result in composite material that would possess elastoplastic characteristics with the matrix and the aggregate providing a defined crushing stress, while the voids in the aggregate provide the plastic deformation. Examples of this are described in Section 3.9.1 which discusses incorporation of natural, artificial, and waste aggregates in a portland-cement matrix. The resulting behavior of these composite materials is shown in Figure 5.29.

5.2 FOAMED PLASTICS

Cellular or foamed plastics are of two general types structurally: the closed-cell or rigid foam type, in which each individual cell, more or less spherical in shape, is completely enclosed by a wall of plastic; and the open-cell or flexible type, in which all of the cells are intercommunicating. The closed-cell or rigid type generally exhibits an elastoplastic stress-strain behavior, as shown in Figures 5.15 to 5.19. The open-cell or flexible type generally exhibits a plastoelastic stress-strain behavior, as shown in Figures 5.20 and 5.21.

There are eight primary chemical types of cellular plastics that could possibly be used as backpacking material: (1) cellulose acetate, (2) epoxy, (3) polystyrene, (4) silicone, (5) urea formaldehyde, (6) urethane, (7) vinyl, and (8) phenolic.

Table 5.1 contains a summary of some of the published information on these plastics that pertains to the backpacking interest (References 22, 23, 25, and 32). From the curves shown in Figures 5.15 to 5.21, it can be seen that the energy absorption, stress transfer, and deformation criteria for a backpacking can be satisfied. The information in Table 5.1, however, indicates that some of the other criteria governing the backpacking selection may be more difficult to satisfy. The properties of any foamed plastic should be given careful consideration when selecting it for use as backpacking. The ultimate selection of the foam should depend upon service conditions (which may preclude some of the desired criteria) and the final cost of the in-place material.

As evidenced from the information in Table 5.1, foamed plastics are available in a wide range of densities and strengths. The constituents of foamed plastic can be selected and formulated to obtain a desired density and strength within the limitations of the basic ingredients.

The constituents, formulation, and mechanical and chemical processes involved in obtaining a foamed plastic will in most cases determine the type of cell structure of the foamed material; the type of cell structure, in turn, determines to a large degree the water-absorption characteristics of the finished material. Heed must also be paid to the constituents of the plastic as water may adversely affect them over long periods of time (Reference 34). When a material is to be used in a water environment, it is important that the percentage of closed cells in the foam be as high as possible since a relation exists between the percentage of open cells in a foam and the water absorption. Water absorption can thus be minimized by careful selection of the ingredients (Reference 35).

In general, foamed plastics are age-resistant in that they do not appear to become stronger once the curing of the resin is completed. Some varieties may, however, exhibit strength deterioration with age when subjected to long-duration adverse environments.

Conflicting data have been published on the strain-rate effect in foamed plastics, but it is generally believed that they are strain-rate sensitive (References 24 and 36 to 41). A foamed plastic under consideration for use as backpacking should be evaluated for this phenomenon before it is used to ensure that its response to increased straining rates is known.

Some foamed plastics cannot be foamed-in-place but must be preformed and fitted around a structure. This may be desirable when the working environment does not lend itself to proper ventilation. In most cases, the blowing agents that cause the expansion of the plastic resin and its added ingredients release only the relatively harmless nitrogen gas; but in some cases, other toxic gases may be given off. It should also be noted that most blowing agents are highly flammable and may even be explosive if proper precautions are not observed (Reference 23).

5.3 FOAMED RUBBER

Figure 5.22 indicates that the bonded foamed rubber generally exhibits a plastoelastic behavior. Investigations (References 24 and 36) have shown that the same type of behavior will be obtained from the gas-blown foamed rubber.

The water-absorption capability of the foamed rubber depends on its cell type. The open-cell variety would take much more water than the closed-cell type. The absorption for the closed-cell variety is generally very low. The absorption of the bonded type depends on the compactness of the mass of rubber pieces forming the variety in question. As closed-cell foamed rubber is normally used in its makeup, it would be expected that the absorption would be low; but if the pieces forming the mass are loosely packed together, water will percolate into the system of voids between the individual pieces.

Foamed rubber is age-resistant within the limitations of the environment in which it is placed. It can be subjected to chemical attack under certain conditions, at which time its strength will deteriorate with age if the chemical attack persists.

Very little information is available as to the sensitivity of foamed rubber to strain-rate effects.

Currently, foamed rubbers cannot be foamed-in-place but would have to be preformed and fitted about a structure. Excellent adhesives have been developed for the purpose of bonding rubber to rubber or, for that matter, bonding rubber to most surfaces.

A point which should be kept in mind is the very resilient nature of foamed rubber. In most cases, it resumes its original volume after being loaded and subsequently unloaded. A structure that is encased in foamed rubber and shock-loaded may tend to oscillate for extended periods of time before finally coming to rest. This behavior would not be desirable.

5.4 CELLULAR METALS

Cellular metals can be made with a number of different types of metals; however, foamed or cellular aluminum appears to predominate when energy absorption is required. The curves shown in Figure 5.23 for the two different mesh aluminums depict an elastoplastic behavior.

As the basic aluminum has a defined strength range, density is used as the governing factor when foamed material is made. The lower densities provide lower strengths and, understandably, higher void contents as the void content controls the density. The converse is true of higher densities. Because the void system is intercommunicating, the possibility of water infiltration would be high. It has not been measured, however, under the conditions that might prevail in a backpacking environment. Foamed aluminum appears to be strain-rate sensitive and is definitely age-resistant. Fabrication-control problems limit the foamed aluminum to small pieces that would have to be stacked and fitted around a buried structure.

5.5 CELLULAR GLASS

As can be seen from the curves in Figure 5.24, cellular or foamed glass generally exhibits an elastoplastic behavior. The material does not appear to be isotropic, however, as there appears to be a considerable difference in the stress levels when the material is tested both parallel and perpendicular to the direction of foam rise.

The cellular glass has a low water absorption; however, long-time effects of increased water pressures are not known. The material appears to be strain-rate sensitive. It is age-resistant with no strength changes occurring once the expanded melt has hardened. It is obvious from the extremely high melt temperatures described in Section 3.6 that the material cannot be foamed-in-place but must be preformed in small pieces that could be fitted around a structure.

5.6 HONEYCOMBS

5.6.1 Paper Honeycombs. Investigations of various types and grades of paper honeycombs have shown them to be effective energy absorbers (References 29, 42, and 43). They exhibit elastoplastic behavior with the crushing stress plateaus generally being less than 100 psi (Figure 5.25). The honeycombs usually bottom and begin to lock up after 60 percent deformation has occurred.

The performance strength of the paper honeycomb depends on the quality of the paper, its resin treatment if any, the cell size, and the type of facing used. The amount of moisture in the material will also be a contributing factor (References 44, 45, and 46). Indications are that the performance strength is also strain-rate dependent (Reference 42).

The thickness of the honeycomb is limited because of manufacturing problems. This means that smaller thicknesses than those required for backpacking a liner may have to be pieced or stacked to obtain the final desired thickness. Rapid loading tests on stacked pieces of paper honeycombs indicate that the response of the stacked pieces is similar to that of a single piece at comparable stress levels (Reference 43).

The type of material (kraft paper) and the basic structural configuration of the honeycomb will probably preclude its use by itself in an environment that may even remotely encounter groundwater. The treatment of the kraft paper with phenolic or other plastic resins and/or the sealing of the honeycomb cell ends with a closed-cell, foamed polyurethane plastic may reduce or eliminate the infiltration of water into the material and the cells. The use of these techniques for this purpose has not been thoroughly investigated, and no degree of certainty of water exclusion can now be attributed to their use.

5.6.2 Metallic Honeycombs. The behavior of metallic honeycombs under load is similar to that of paper honeycombs. They also exhibit elastoplastic behavior (Figure 5.26) but with crushing-stress plateaus generally greater than those of the paper honeycombs (References 47, 48, 49, and 50).

The performance of the metallic honeycomb depends on its fabrication. Various foil thicknesses, corrugation heights, and lamination patterns can be combined to design a honeycomb that will satisfy the load and energy requirements of a given application. Generally, however, the crushing stress of a metallic honeycomb is a function of the density of the honeycomb.

As in the case of the paper honeycombs, metallic honeycombs are limited in size and would have to be stacked or placed around a buried structure.

The construction of the metallic honeycomb makes it highly susceptible to groundwater infiltration; however, the absorption of water by the basic material itself is nil. The metallic honeycomb is age-resistant. Whether or not it is strain-rate sensitive is not clearly defined in the published literature, but indications are that if the material is strain-rate sensitive, the resulting difference is very small.

5.7 FOAMED SULFUR

Foamed sulfur is a recent development primarily designed to complement the family of materials that could possibly be used as backpacking. The basic sulfur foam formulations and resultant properties of the foams have not been fully optimized as of this writing; however, the preliminary information available (References 27 and 28) indicates that the material, with further development work, could be satisfactorily used as backpacking.

The foamed products resulting from the initial development work possess a good cell uniformity with compressive strengths varying from 125 to over 500 psi. Figure 5.27 shows two curves for different foam formulations. The curves generally depict elasto-plastic behavior. For most of the samples evaluated, locking of the material does not appear to occur until 40 to 70 percent deformation, depending on void content, has occurred. As can be seen in Figure 5.28, strengths can be varied by varying the density (changing the void content) or by changing the foam formulation.

Water absorption as low as 10 percent has been measured after submergence under water at 50 psig for 24-hour periods. No long-term submergence information is available. The long-term effect of water on the foam constituents also is not known.

Based on the behavior of the basic ingredients of the foam, it seems feasible that the material will be age-resistant; however, this phenomenon has not been evaluated. Limited testing at the Concrete Division of the U. S. Army Engineer Waterways Experiment Station has shown that the foamed sulfur is strain-rate sensitive.

Unfortunately, the present foam formulations are not odorless. The odor does not affect the physical properties of the material but does develop an unpleasant working environment. The odors are generated by currently used plasticizers, and indications are that odorless foams could be produced using more suitable plasticizers.

Additional development work has shown that foamed sulfur can be produced on a continuous basis with equipment that is simple and capable of being scaled up to any size. A pilot model of the equipment has been developed and has proved successful. Foamed sulfur can also be sprayed on some surfaces (Reference 28).

5.8 LOW-DENSITY CONCRETES

The low-density concretes investigated in this study generally exhibit an elastoplastic behavior (Figures 5.29 and 5.30). The strength of the hardened matrix and, in part, the strength of the aggregate in most cases where aggregate is used contribute to the development of a defined crushing point of the material. After initial crushing has begun, the voids in the aggregate and/or other voids in the matrix begin to collapse, thus allowing the concrete to deform at no appreciable increase in stress level.

The crushing-stress plateau of the cellular concretes (Figure 5.30) appears to be flatter than the plateau of the low-density aggregate-type concretes (Figure 5.29). The progressively locking plateau of the low-density aggregate-type concretes may be due to the presence of the aggregate and its contribution, if any, to the overall strength of the concrete. If an aggregate is used in the portland-cement matrix, it should be very weak and friable and contain a large number of collapsible-type voids. Experience has shown that the addition of too much aggregate into a matrix in order to obtain more deformation adversely affects the workability of the concrete. The solution is that most insulating concretes, such as vermiculite (References 8, 39, 51, and 52) and perlite (References 18 and 19), require as much as 20 to 30 percent entrained air in order to be suitable for backpacking use. Cellular concretes (References 19 and 53), which may or may not contain a fine sand or filler, can often be found with air contents as high as 75 percent of the total concrete volume.

These air voids, while desirable from the point of view of deformation, tend to absorb moisture when it is available from the surroundings. The water-filled voids would, of course, reduce the effectiveness of the backpacking system. Tests (Reference 53) have indicated that very large water pressures are necessary to saturate these concretes over a short period of time, but the long-time saturation effect of a considerably smaller pressure is not known. When the concretes are removed from the water-pressure environment they appear to drain freely and to reach a point considerably less than complete saturation.

The low-density concretes appear to be strain-rate sensitive and generally are not age-resistant. The increase in the strength of the concrete with age is influenced by a number of additional factors so that strength gain, if any, cannot be predicted until the actual jobsite conditions are known.

A large number of low-density aggregates such as those discussed in Section 5.1, along with varying air contents and possible additions of fillers, could be utilized in a portland-cement matrix to produce a low-density concrete. The type of low-density aggregates and mixture designs must be established by experimentation. Generally, most low-density concretes of both types discussed in this investigation can be fabricated and placed in most environments using conventional construction equipment.

5.9 MULTIPLE-SHOT LOADING CAPABILITY

The multiple-shot loading capability of the materials investigated herein has not been discussed because very little work has been done in this area with these materials. Specifically, the problem is: If a backpacked structure has survived an initial loading of a single weapons burst, what are the chances that the structure will survive additional loadings occurring in the same locale at varying time intervals?

If the structure survives the effects of the first loading and the deformations of the cavity walls were within the elastic strain region (Figure 2.6) of the medium, the backpacking should retain almost all of its original potential; if the deformations of the cavity wall were in the elastoplastic strain region (Figure 2.6) of the medium, partial closure of the cavity probably resulted (Figure 2.10). Assuming the backpacking does not lock under the initial loading and partial closure of the cavity, some of the potential of the backpacking theoretically should be available for additional loading. It is doubtful that the backpacking would be able to rebound and regain any appreciable amount of its original volume as the forces in the backpacking would not be great enough to force and compact the crushed rock into some semblance of its original form.

After the initial loading, assuming partial closure of the cavity has occurred, it is unlikely that the backpacking would achieve its original state of stress before loading because of the dead load of rock mass it would now have to support. Given sufficient time, the backpacking would probably attempt to creep out from under any stress concentrations, thus resulting in a somewhat uniform stress throughout the material. The time it would take to accomplish this, if at all, would depend on the properties of the material in question.

The portion of the remaining unlocked backpacking, then, is the area of interest for multiple-shot loading of a single-material backpacking system. Little published information has been located on behavior of the materials mentioned herein when reloaded after being partially failed. It is hoped that the materials used as backpacking, when reloaded, will resume the same stress plateau of the original loading and continue until locking begins to occur. This behavior should be proven for any material contemplated for actual use as a backpacking.

5.10 ECONOMIC CONSIDERATIONS

No detailed examinations of the costs of the various materials that could possibly be used as backpacking can be made in a report of this nature as the ultimate in-place cost of any material will depend on the (1) basic material cost which will be related in most cases to the volume of material required, (2) availability which would be related to shipping costs, (3) storage and handling costs, and (4) placing costs which would include men, materials, and equipment. All of these factors will vary from job to job and will be influenced by the actual material used.

The materials discussed in this report are only representative samples of what could conceivably be used as backpacking under a given set of conditions. The actual materials discussed are compared on a relative cost basis in Figures 5.31 to 5.34. All values shown are relative to the other values in the same figure. These values are general and approximate and should not be construed as absolute or binding values. They are presented solely to give the reader an idea of the relative costs of the materials in this study. The values used in deriving Figures 5.31 and 5.33 were obtained from the sources from which the materials cited were obtained. The values in Figure 5.32 were obtained from Reference 25.

The values in Figures 5.31 to 5.34 are expressed as the relative cost per unit volume of material. Many of these materials are sold on a unit-weight basis but for the sake of this presentation have been equated to a volume basis for the range of backpacking interest in order that a more realistic comparison of the costs for a volume job could be made.

As can be seen in Figure 5.31, the expanded naturally occurring aggregates appear to cost less than the granular materials produced artificially. Some scrap items, however, compare favorably costwise with the expanded naturally occurring aggregates.

Most foamed plastics are in the same general cost range as can be seen in Figure 5.32. The actual cost of any foamed plastic would depend on basic solid material costs and the density that is desired in the foamed plastic.

Figure 5.33 includes the remainder of the materials in the investigation not mentioned in Figures 5.31 and 5.32. From this figure it can be seen that the foamed sulfur and low-density concretes generally cost less than the other materials in that grouping.

In Figure 5.34 typical materials from each of the major material groupings of this report are compared on a relative cost-per-unit-volume basis. From this figure it appears that the expanded natural aggregates and the lower densities of certain types of low-density concretes are the most economical from a materials cost standpoint, while the foamed plastics and the upper density range of the low-density concretes cost more for the same unit volume.

TABLE 5.1 SUMMARY OF PUBLISHED INFORMATION ON FOAMED PLASTICS

Material	Density	Compressive Strength	Water Absorption	Fabrication		
				Foam-in-Place	Spray	Molded
	pcf	psi				
Cellulose Acetate	6 - 8	125	Low			X
Epoxy						
Preformed	5 - 38	50 - 6,000	Low			X
Pack-in-place	15 - 25	600 - 3,000	Low		X	
Foam-in-place	5 - 8	82 - 110	Depends on cell type	X		
Polystyrene						
Molded beads	1 - 10	20 - 220	Low			X
Reaction type	1.3 - 4.5	35 - 185	Low	X[a]		
Silicone						
Powder type	12 - 16	100 - 325	Low	X		X
Resin type	3.5 - 4.5	0.1 - 8.0	Low	X		X
Elastomeric type	7 - 15	3 - 5[b]	High	X	X	X
Urea Formaldehyde	0.5 - 1.5	1.5 - 5	Very high	X		X
Urethane						
Flexible, molded	1.5 - 4	0.2 - 2.0[c]	Very high			X
Flexible, foam-in-place	2 - 20	0.3 - 4.0[c]	Very high	X	X	
Rigid	1.5 - 18	15 - 1,100	Low	X	X	X
Vinyl						
Flexible	3 - 10	1.5 - 8[b]	Very high			X
Rigid	4 - 25	80 and up	Low			X
Phenolic	0.4 - 20	0.8 - 1,100	High	X		X

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[a] See Reference 33. At the time of this writing, process is not yet commercially available.

[b] Compressive strength at 50 percent deflection.

[c] Compressive strength at 25 percent deflection.

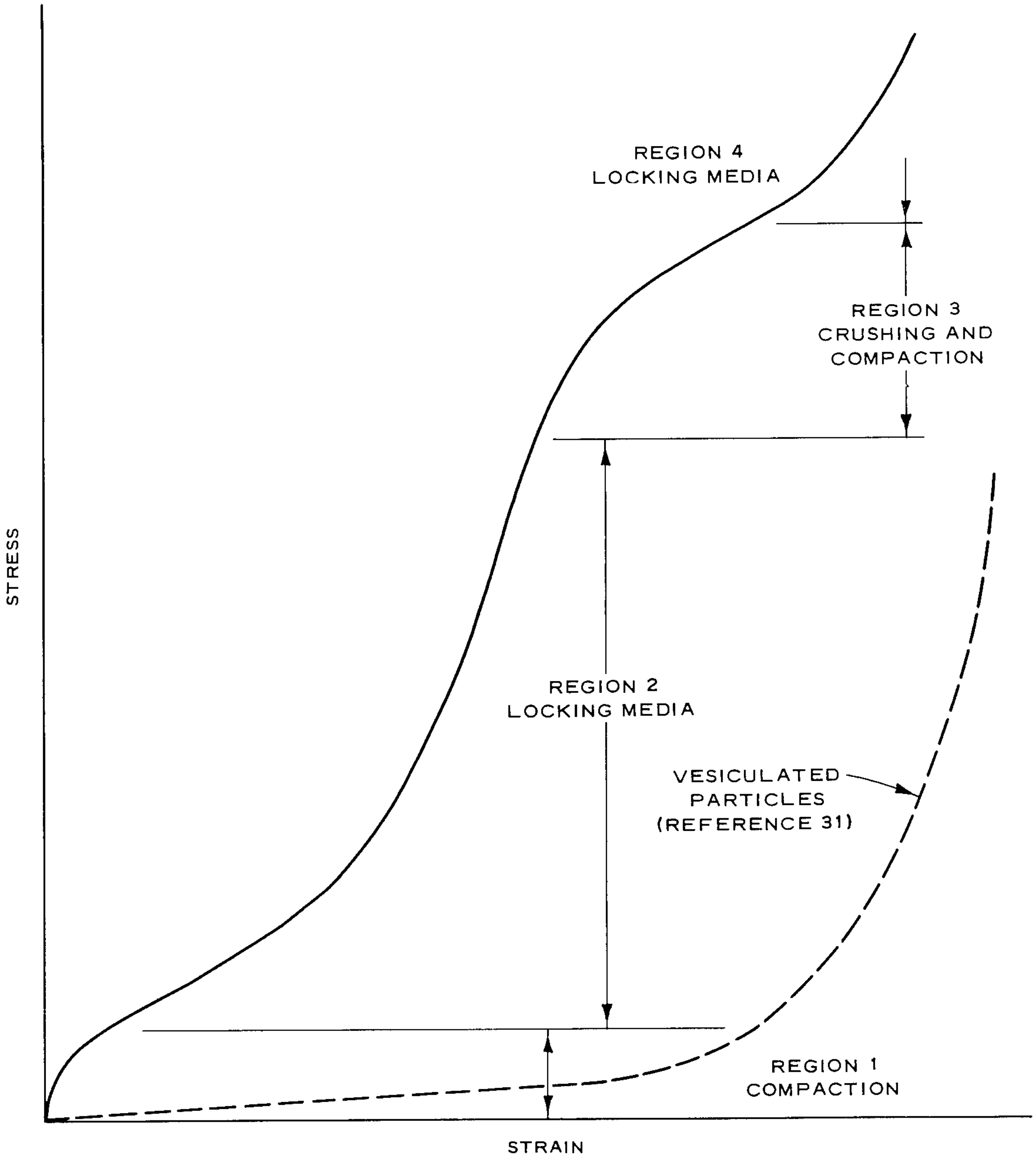

Figure 5.1 Qualitative one-dimensional stress-strain curve for granular material (Reference 30).

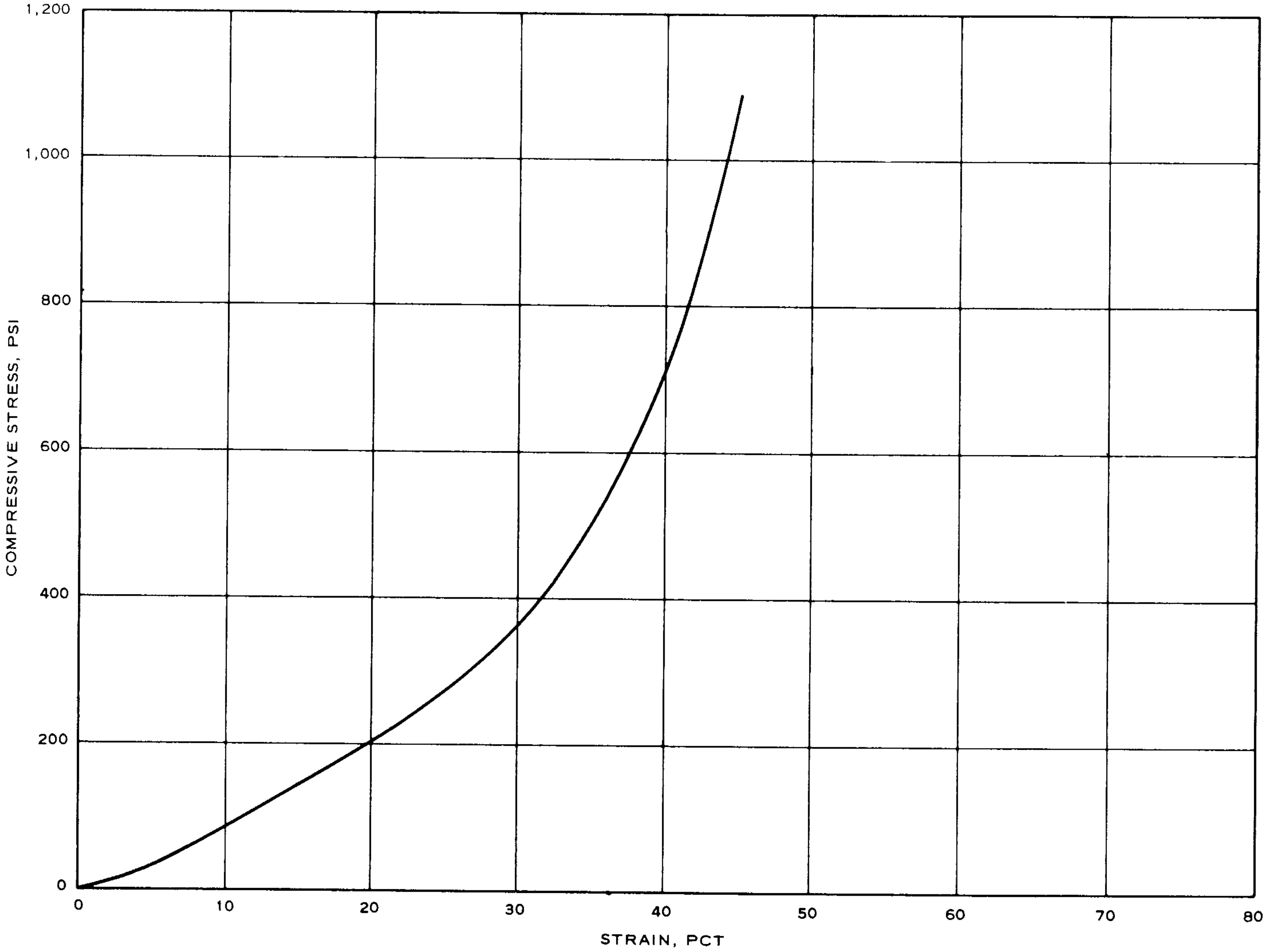

Figure 5.2 Stress-strain curve for volcanic cinders, bulk density 47.9 pcf.

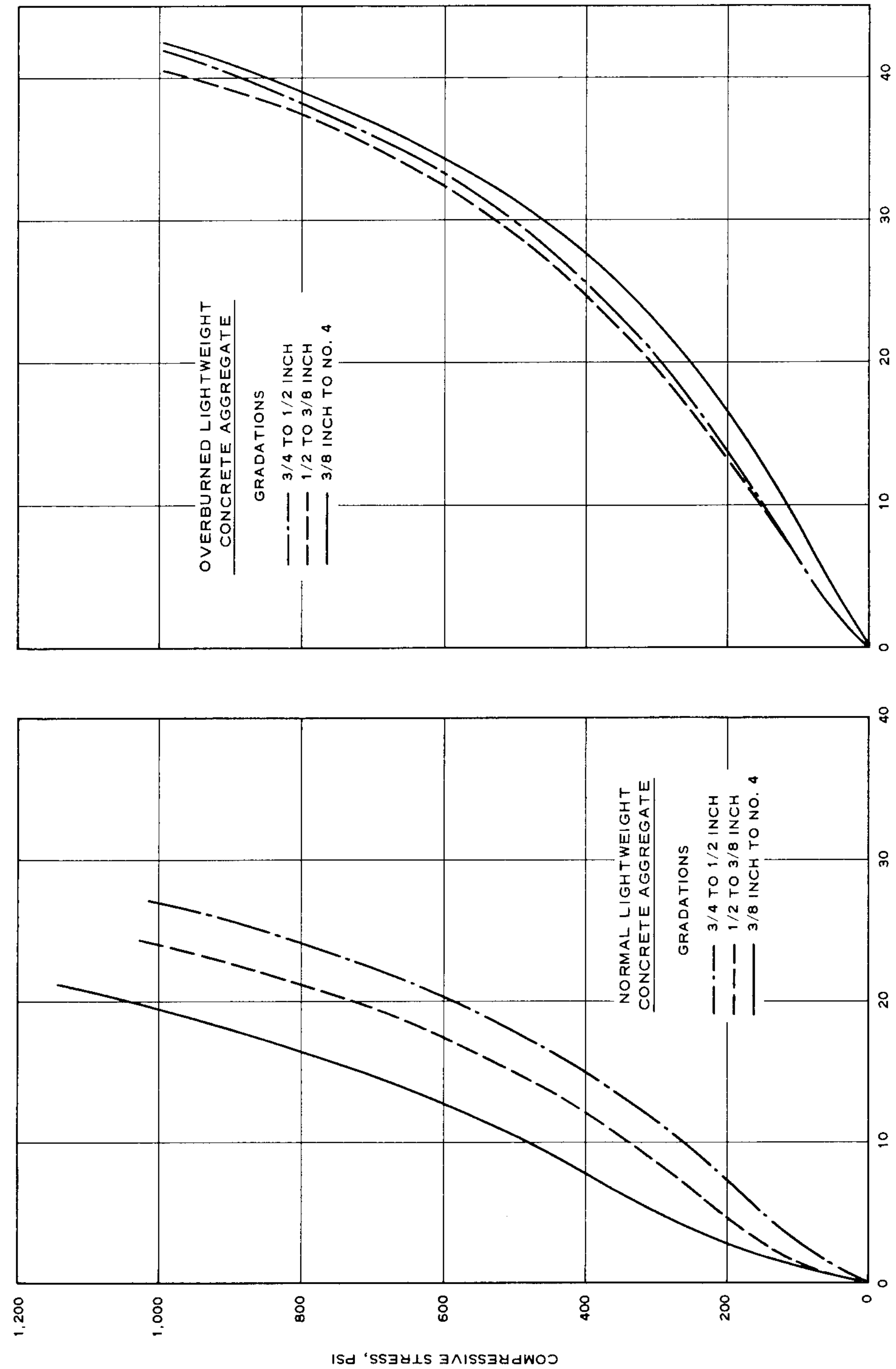

Figure 5.3 Stress-strain curves for expanded clay aggregate.

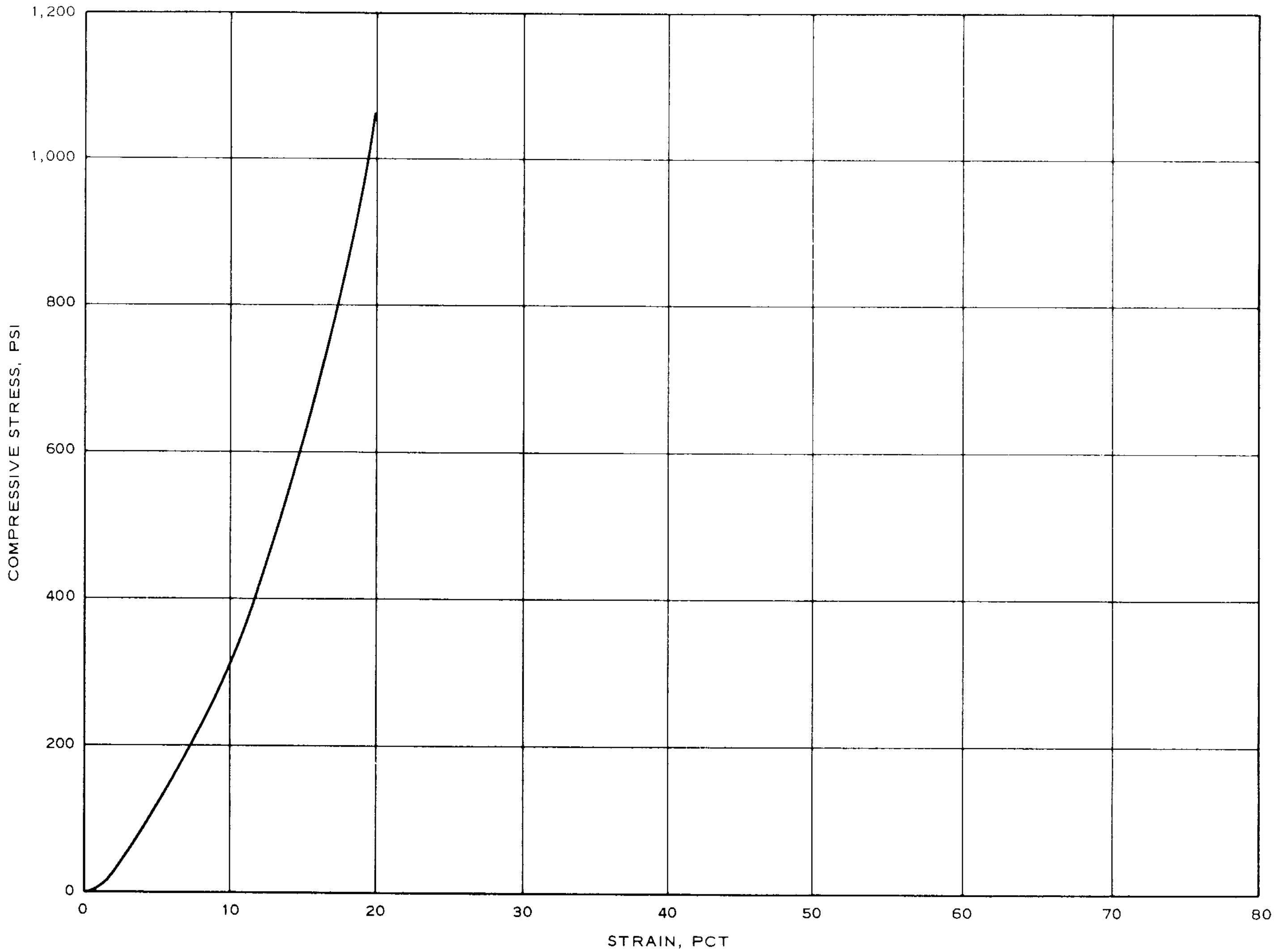

Figure 5.4 Stress-strain curve for expanded shale aggregate, bulk density 49.5 pcf.

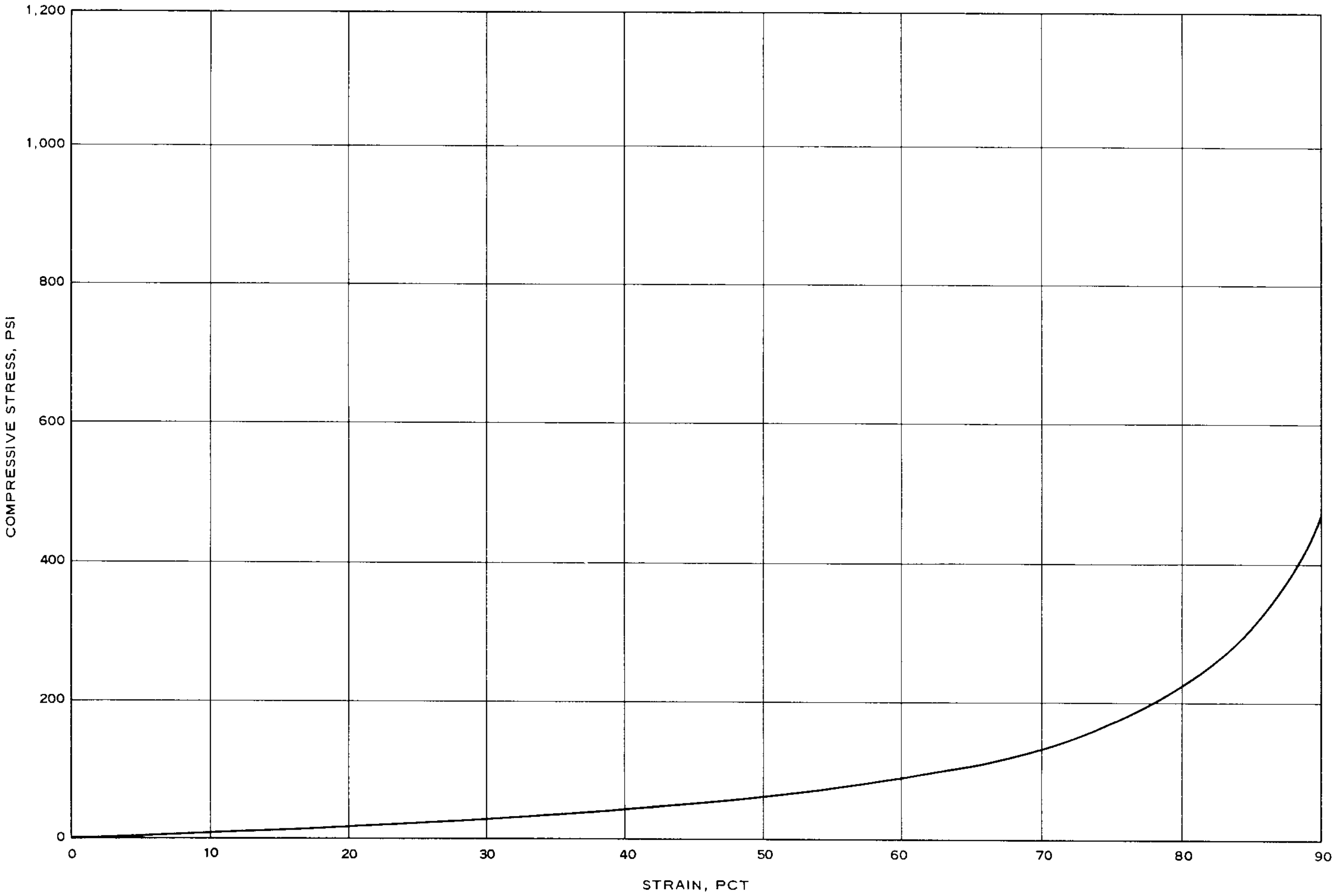

Figure 5.5 Stress-strain curve for expanded vermiculite aggregate, bulk density 8.0 pcf

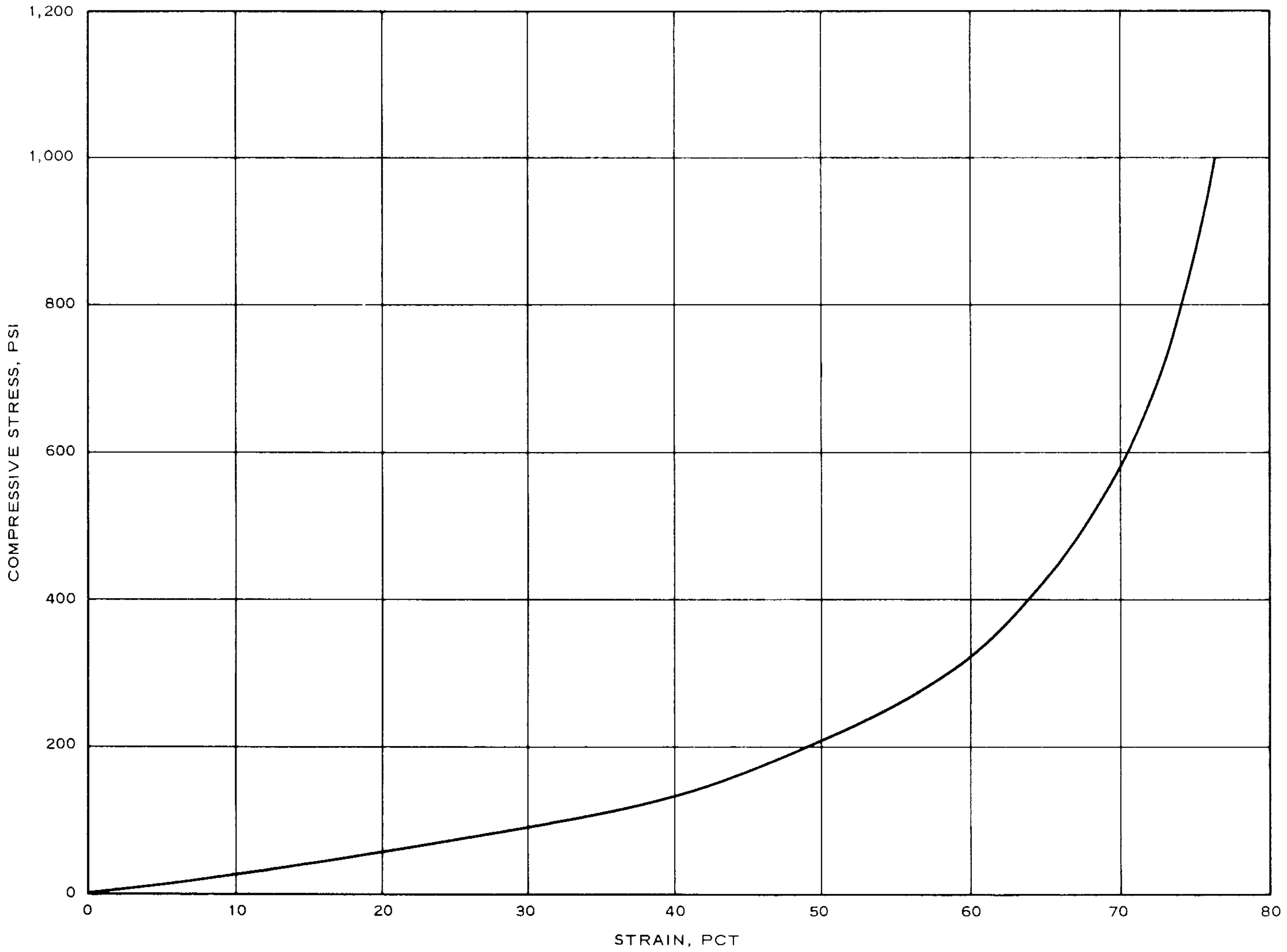

Figure 5.6 Stress-strain curve for expanded perlite aggregate, bulk density 10.2 pcf.

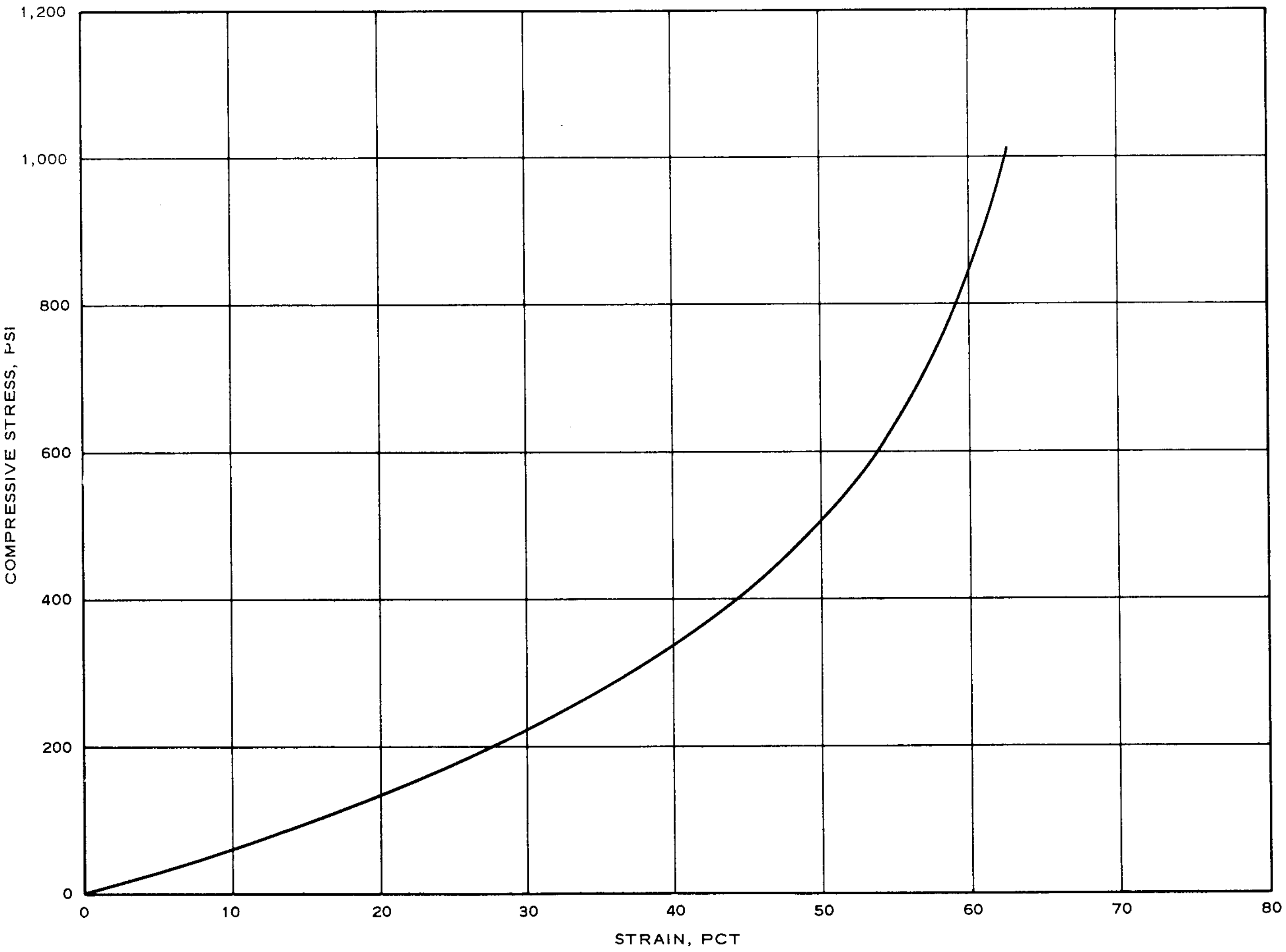

Figure 5.7 Stress-strain curve for phenolic microballoons, bulk density 8.3 pcf.

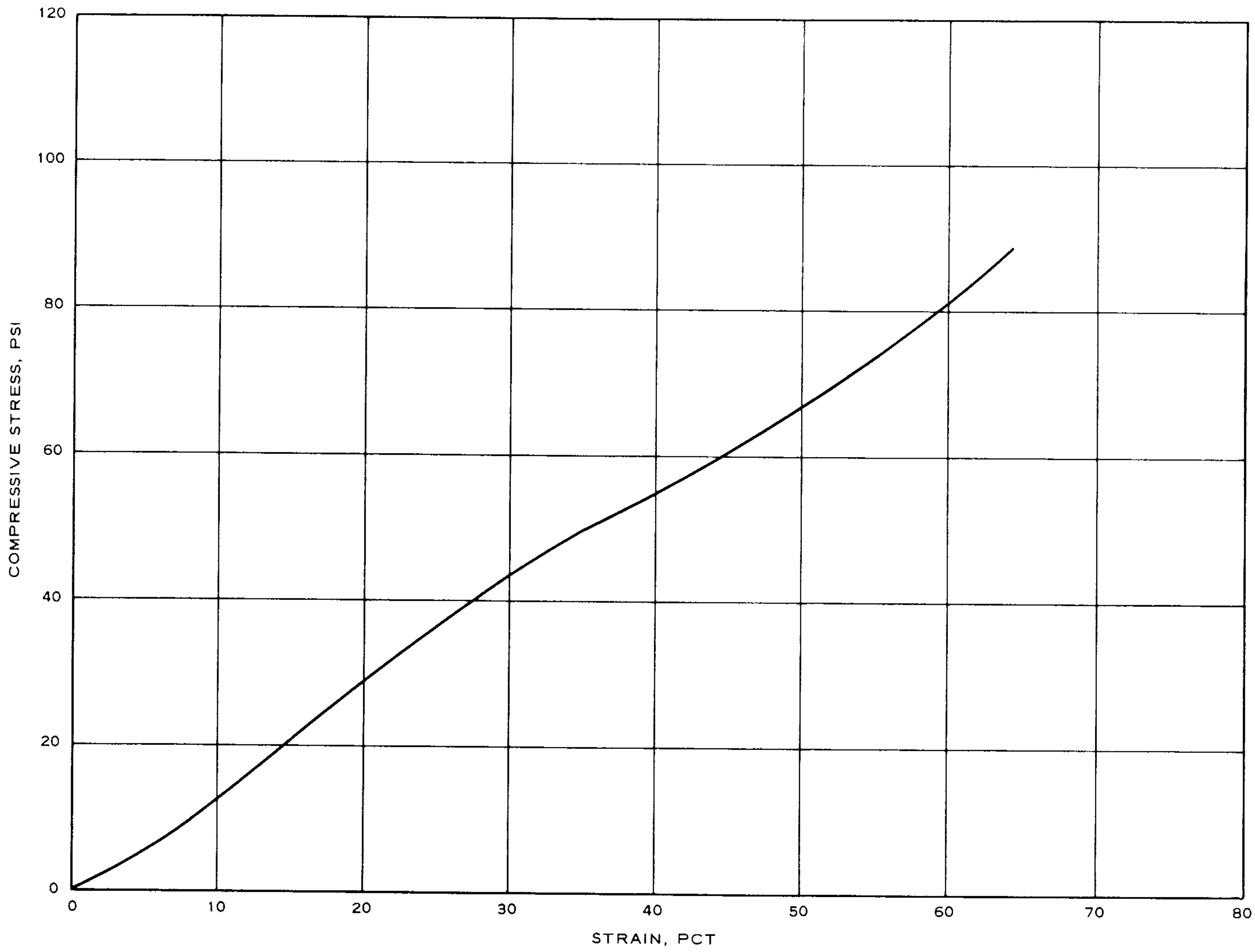

Figure 5.8 Stress-strain curve for expanded polystyrene beads, bulk density 2.0 pcf.

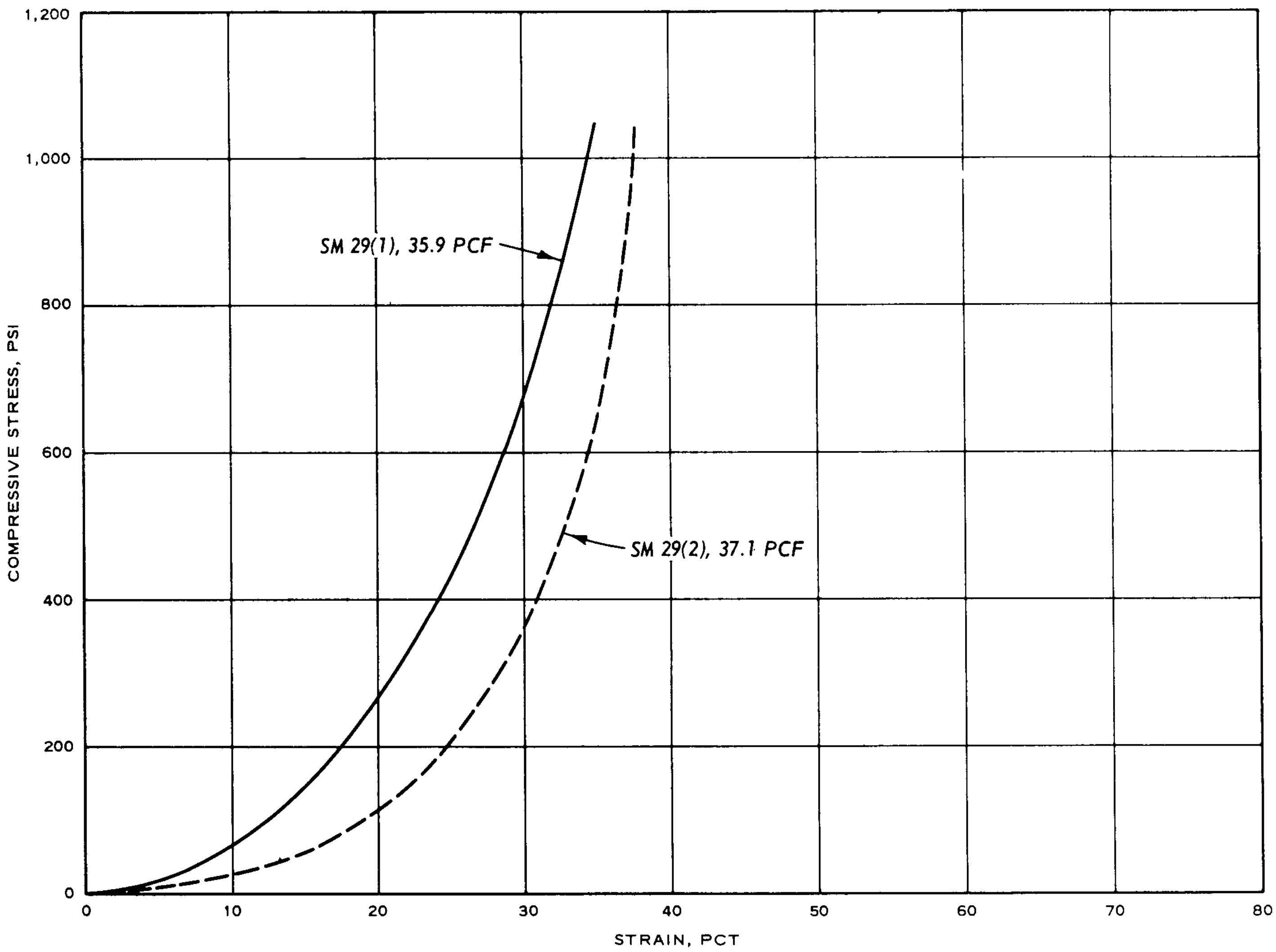

Figure 5.9 Stress-strain curves for ethylene-vinyl acetate copolymer beads.

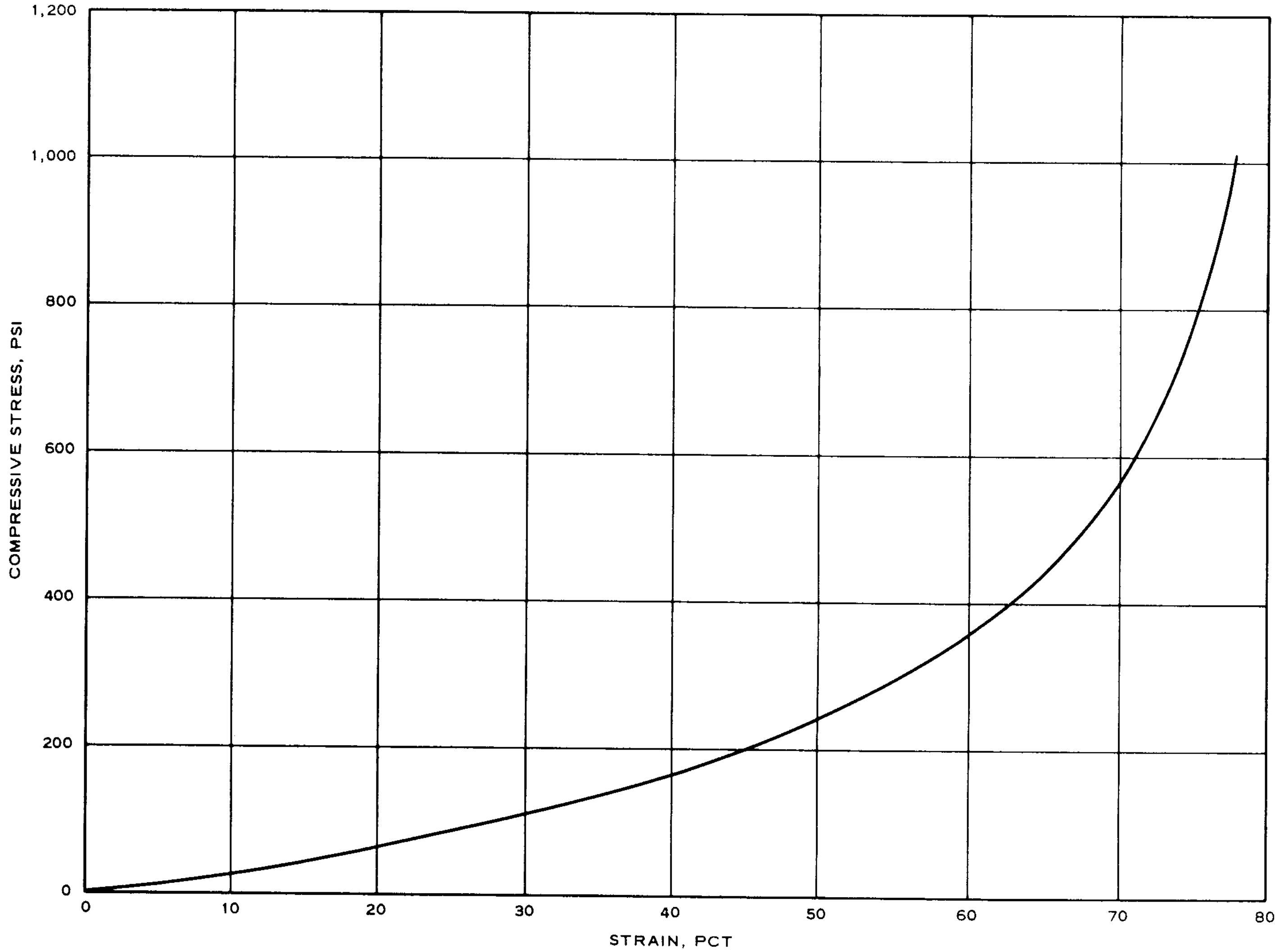

Figure 5.10 Stress-strain curve for foamed aluminum aggregate, bulk density 9.0 pcf.

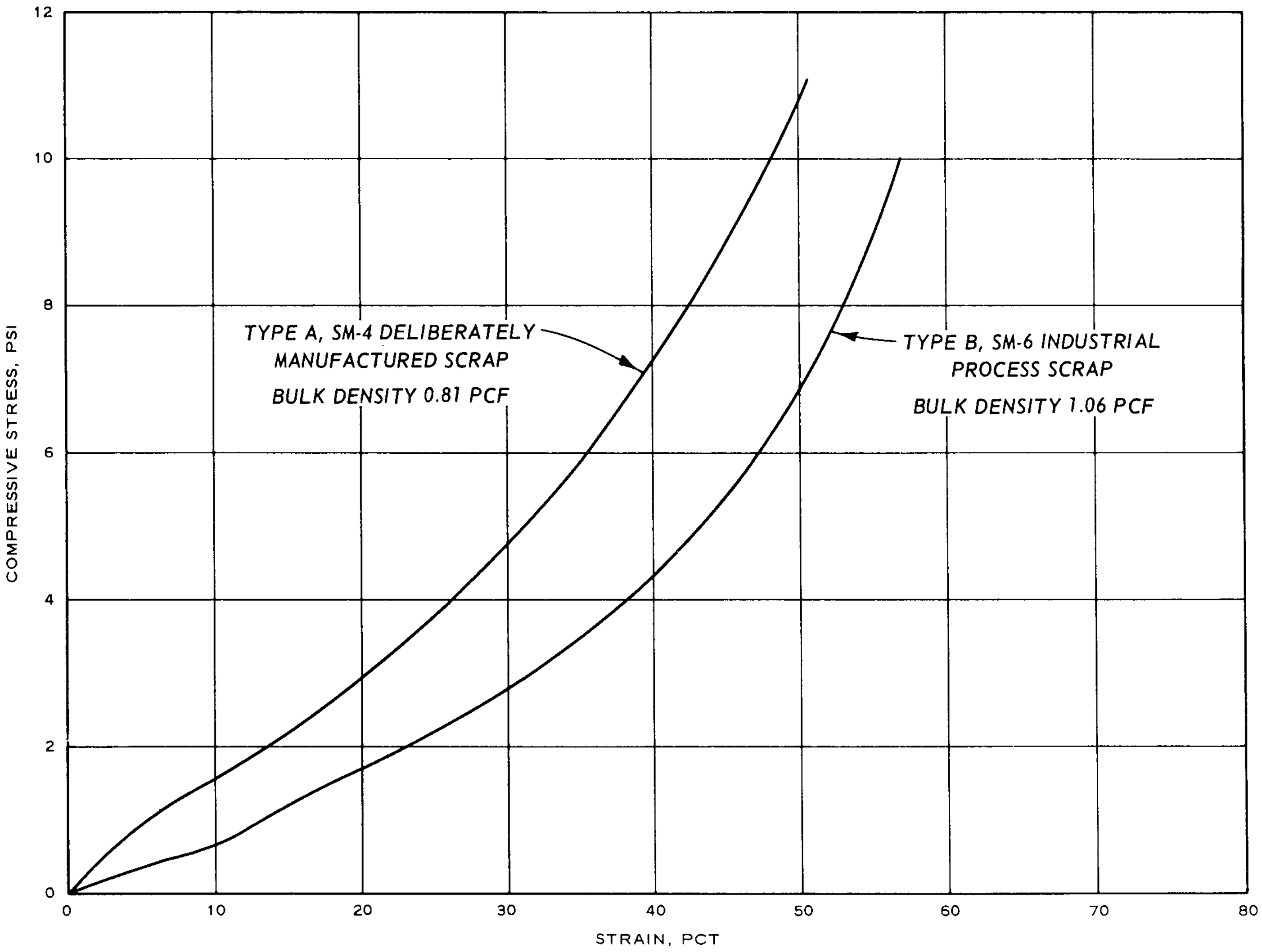

Figure 5.11 Stress-strain curves for expanded polystyrene plastic scrap aggregate.

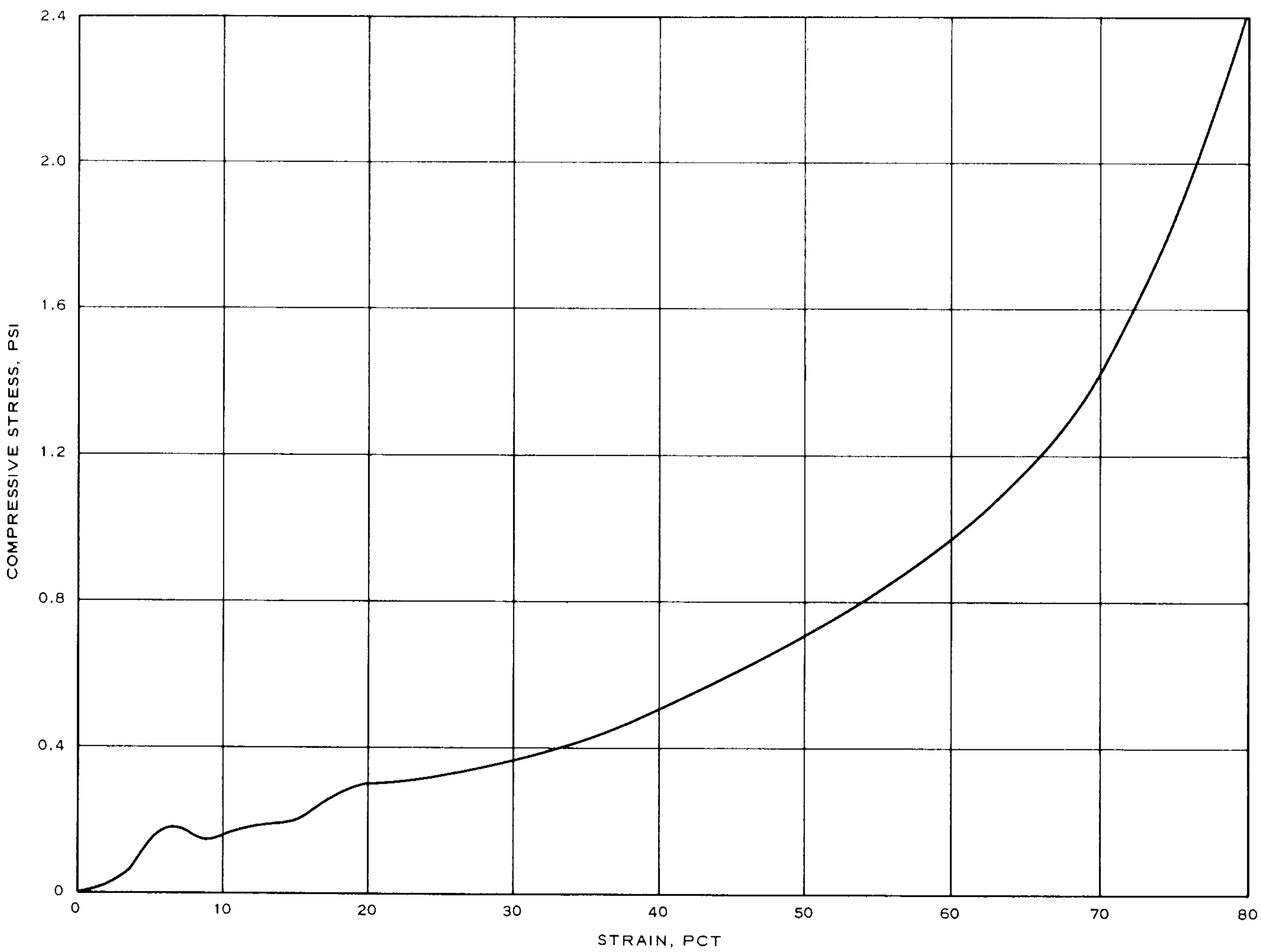

Figure 5.12 Stress-strain curve for expanded polyvinylchloride plastic scrap aggregate, bulk density 0.35 pcf.

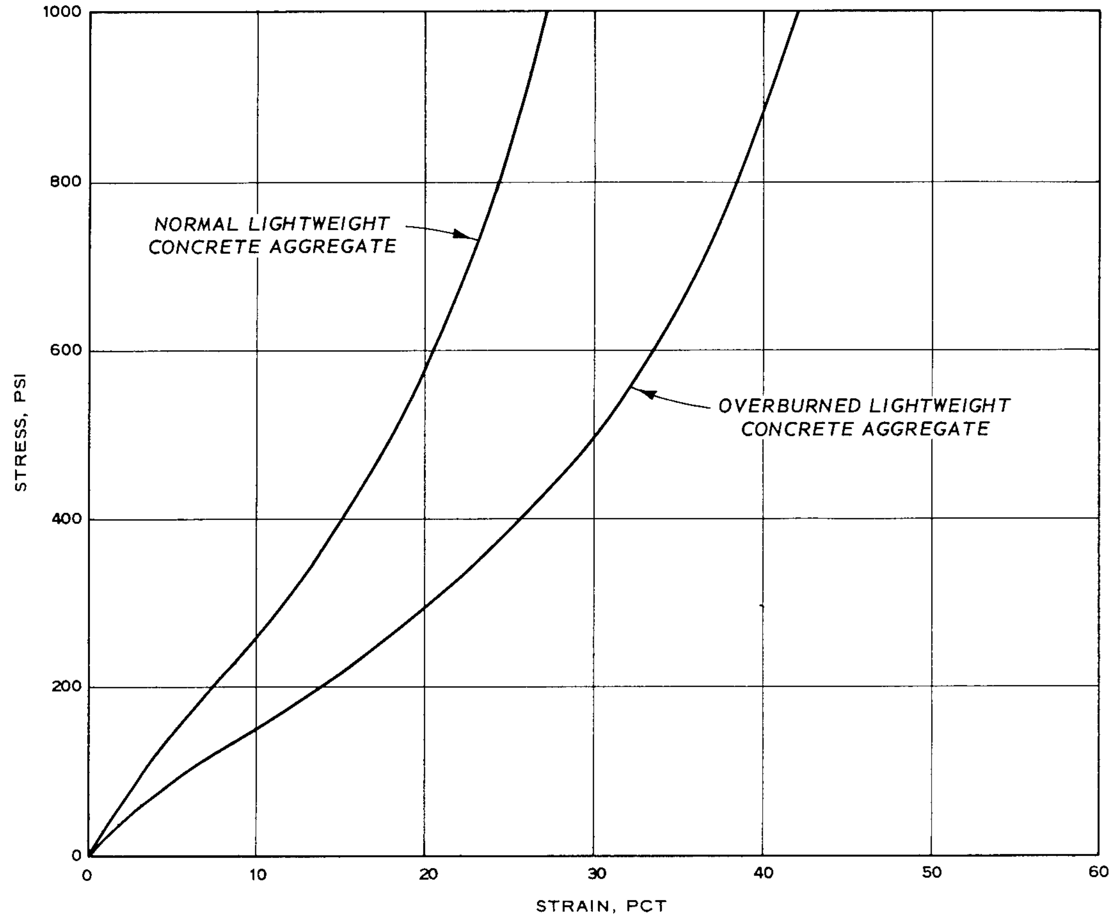

Figure 5.13 Comparison of stress-strain curves for normal and overburned 3/4- to 1/2-inch expanded clay aggregate.

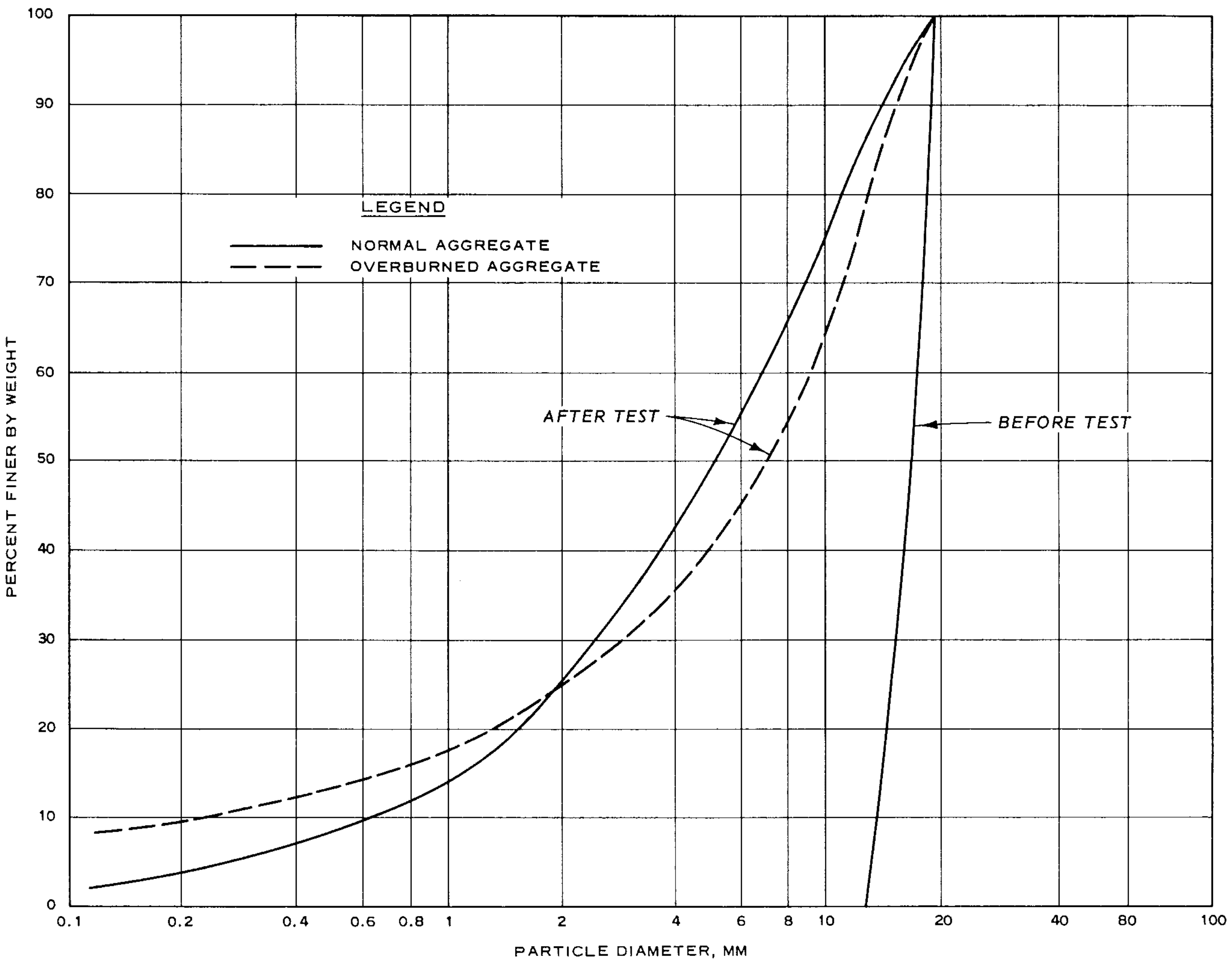

Figure 5.14 Gradation curves for 3/4- to 1/2-inch lightweight expanded clay aggregate.

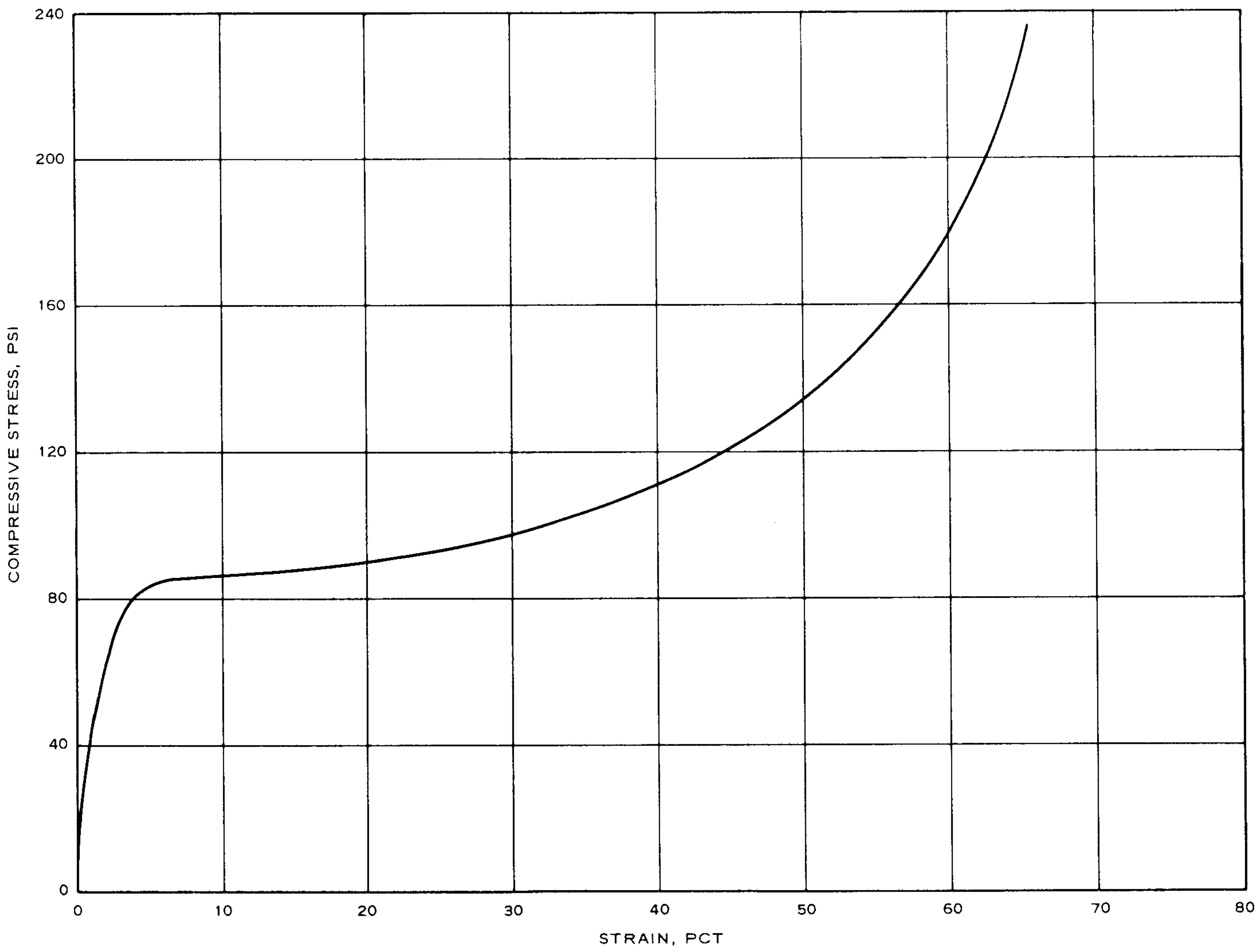

Figure 5.15 Stress-strain curve for rigid epoxy foamed plastic, density 5 pcf.

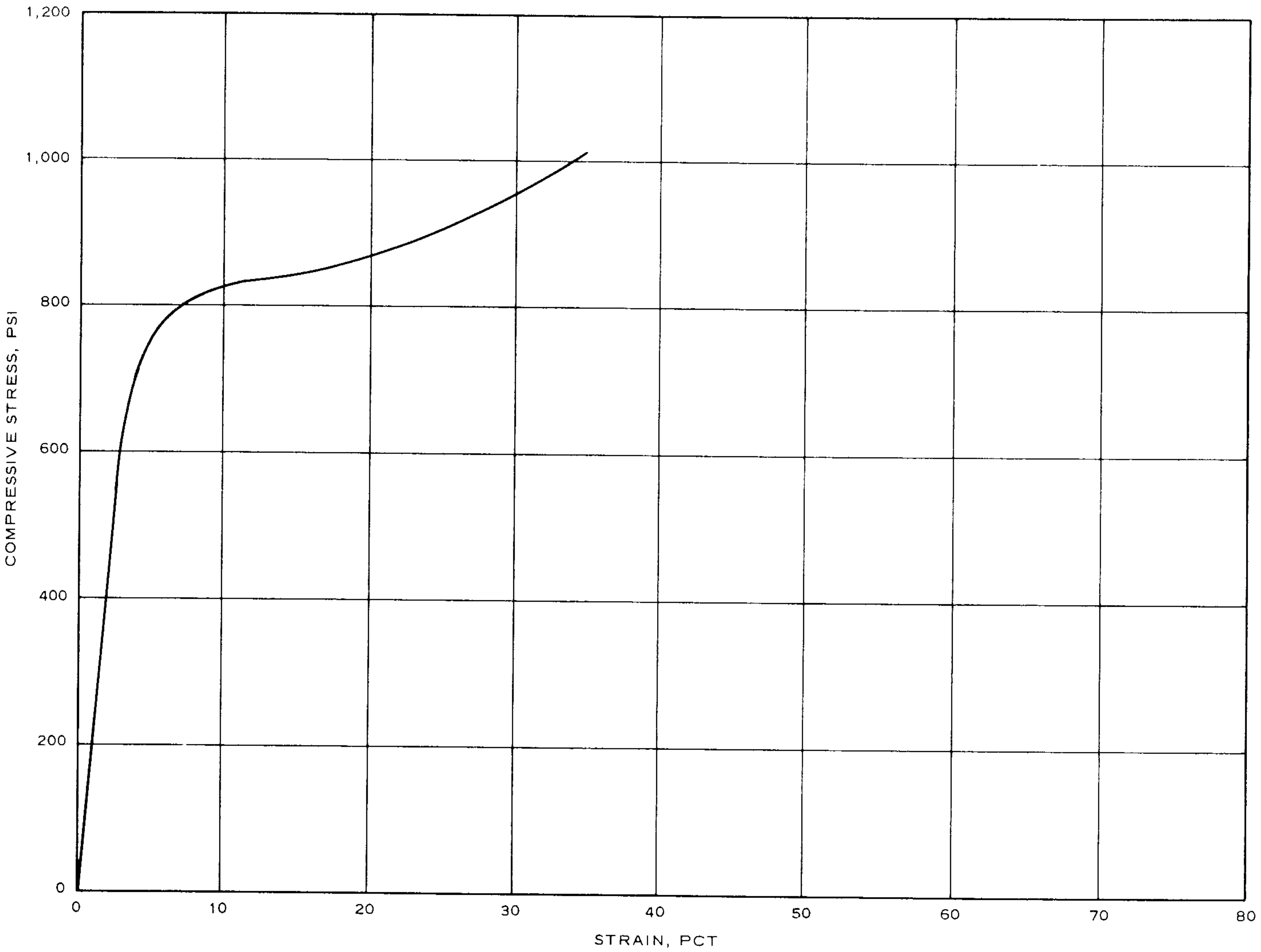

Figure 5.16 Stress-strain curve for rigid expanded phenolic foamed plastic, density 15 pcf.

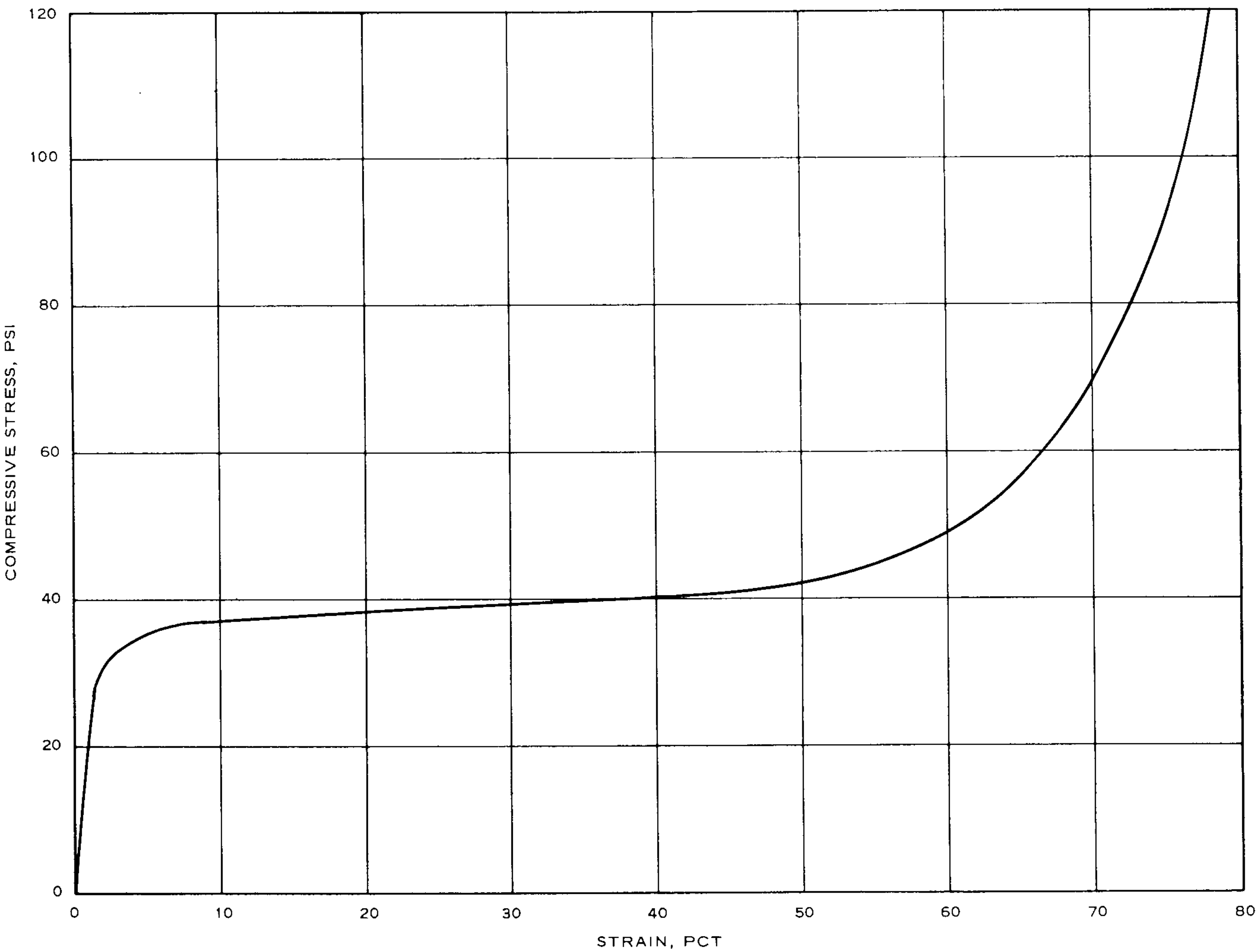

Figure 5.17 Stress-strain curve for rigid cellulose acetate foamed plastic, bulk density 6.4 pcf.

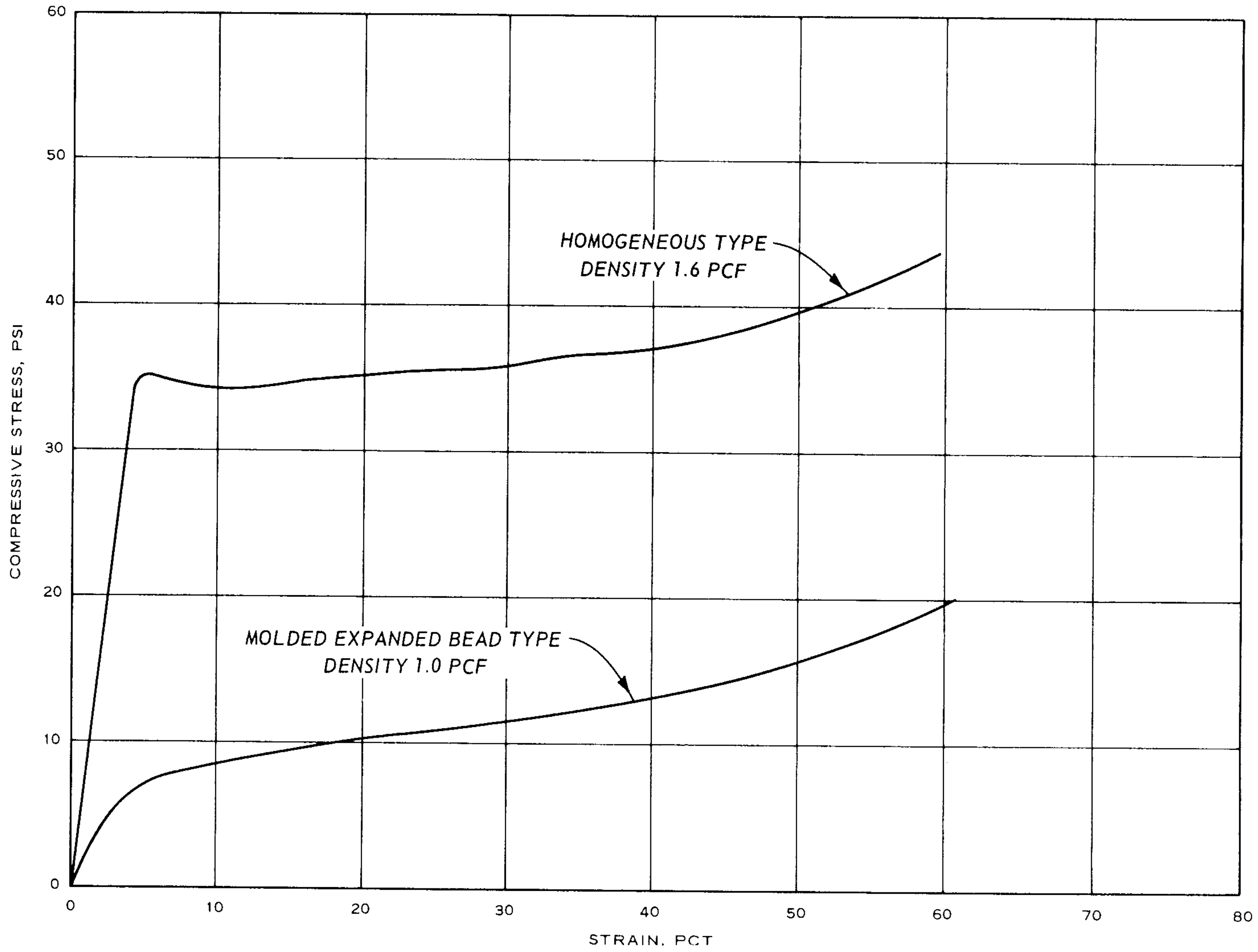

Figure 5.18 Stress-strain curves for rigid polystyrene foamed plastics.

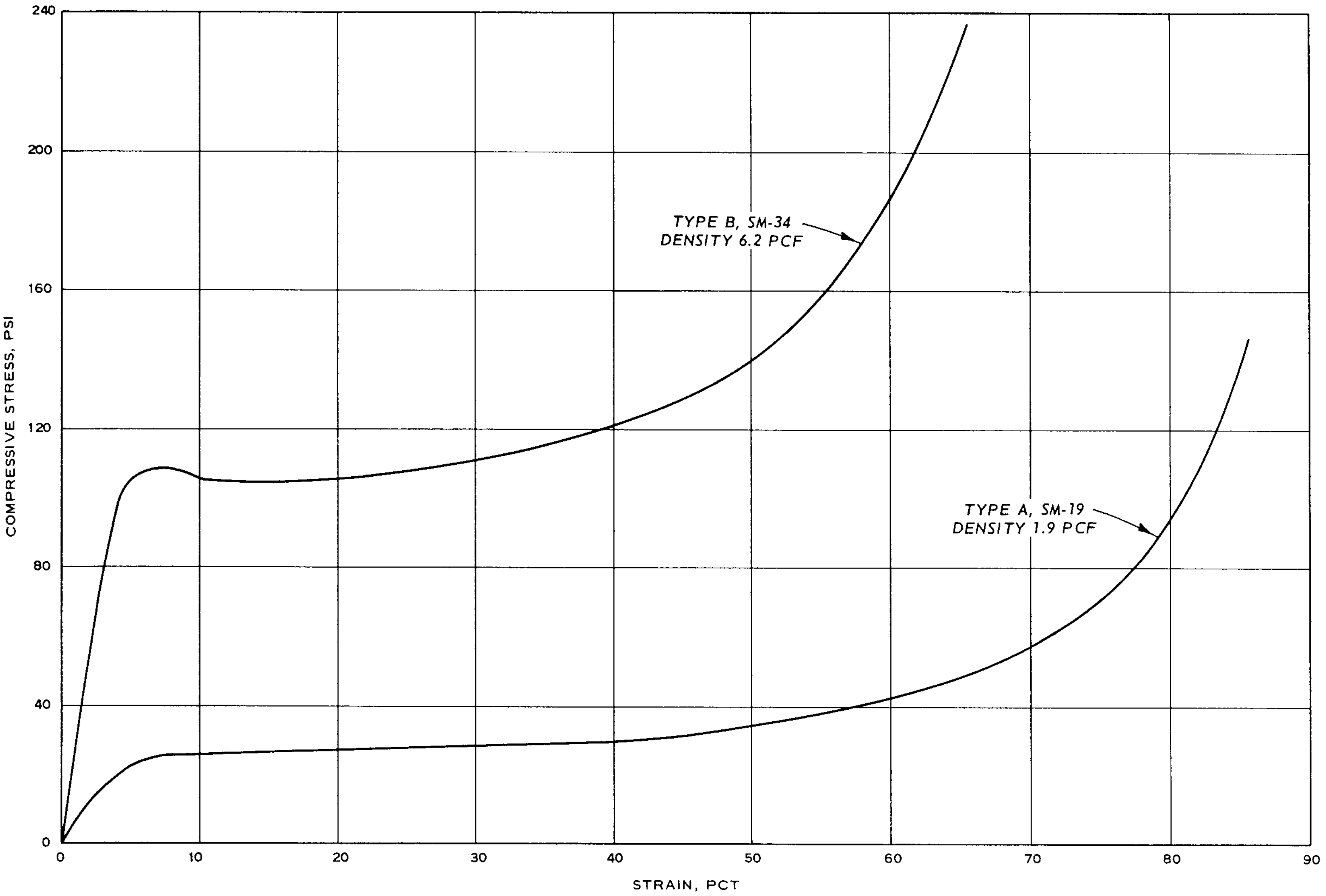

Figure 5.19 Stress-strain curves for rigid expanded polyurethane foamed plastics.

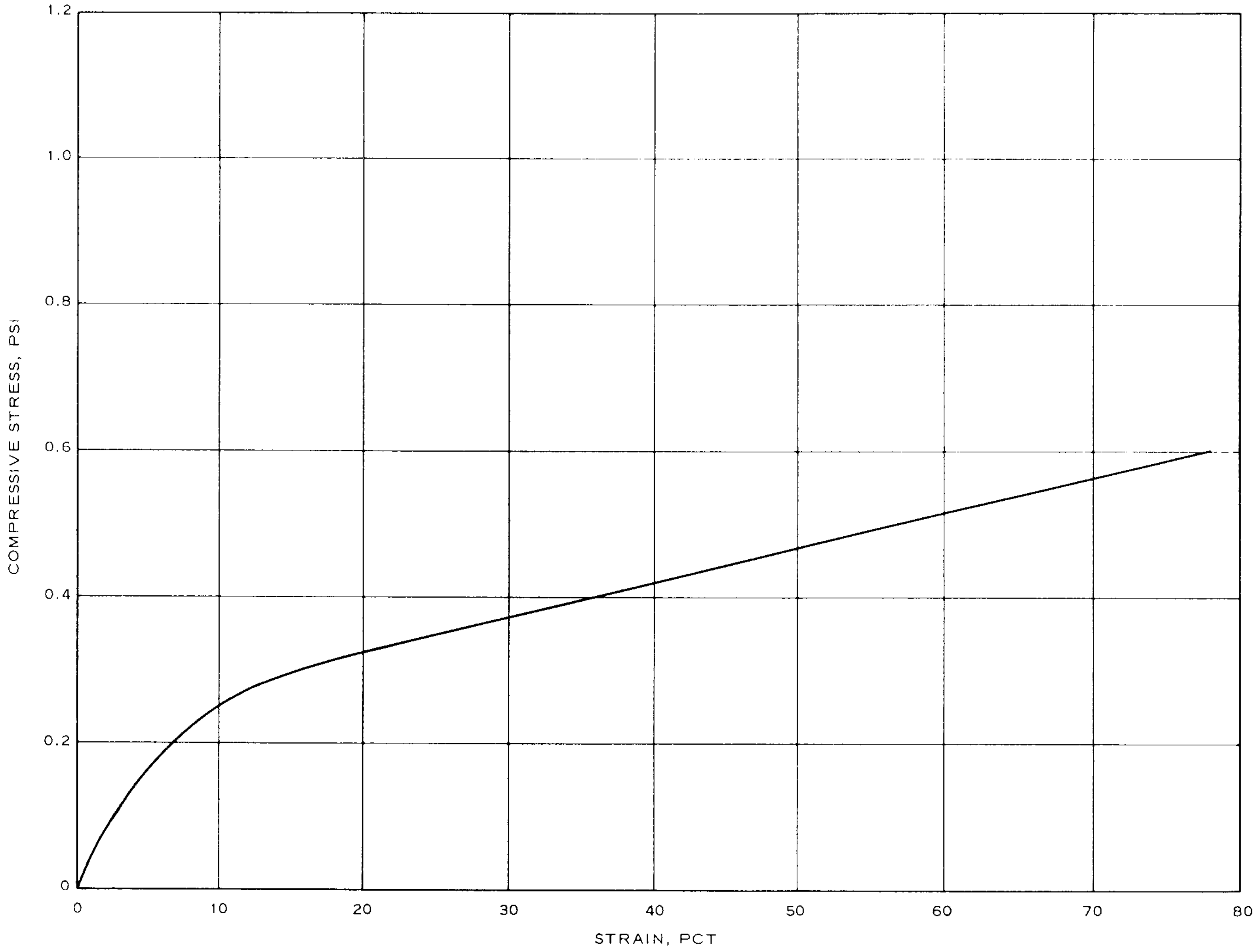

Figure 5.20 Stress-strain curve for flexible expanded polyvinylchloride foamed plastic, density 3.0 pcf.

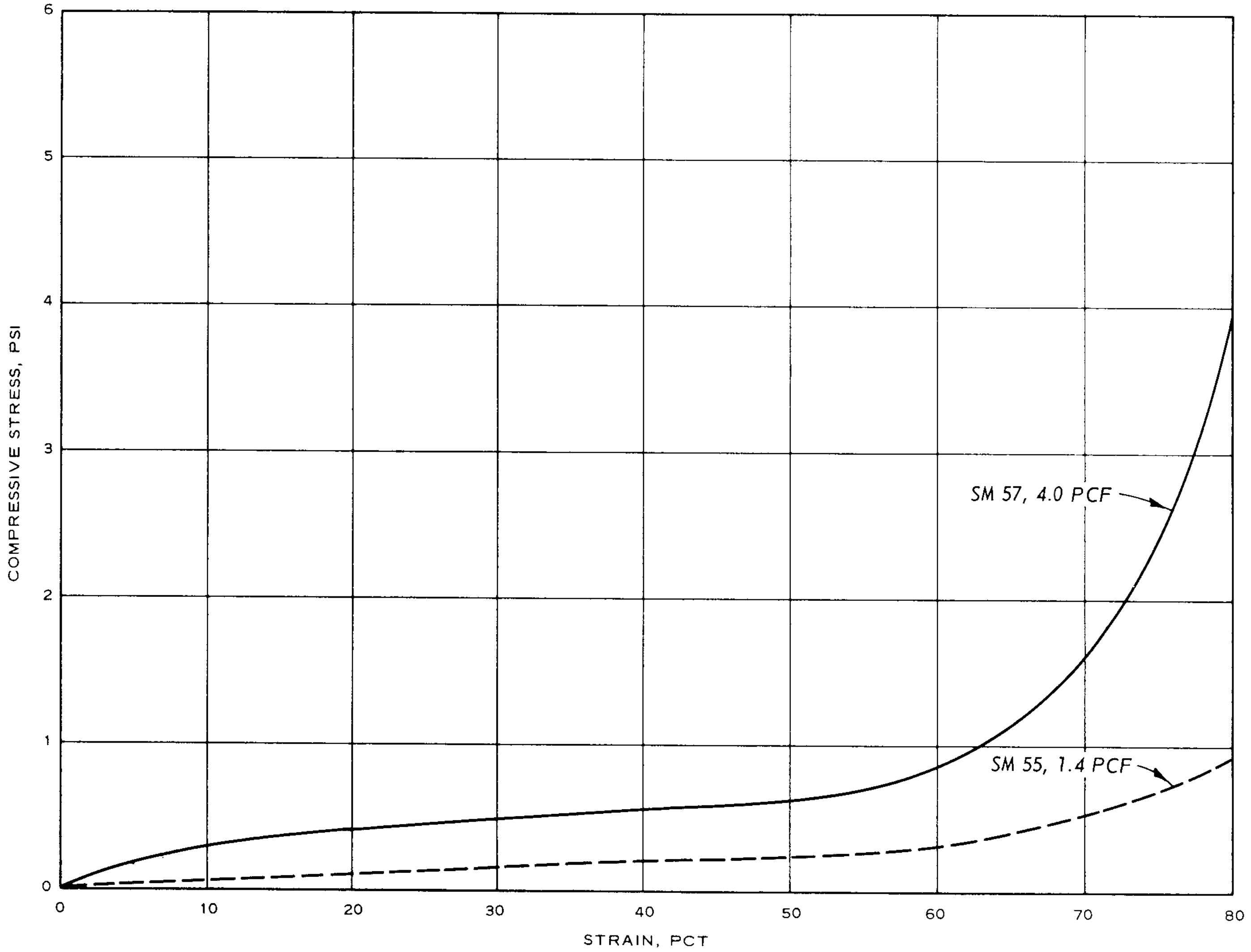

Figure 5.21 Stress-strain curves for flexible polyurethane foamed plastics.

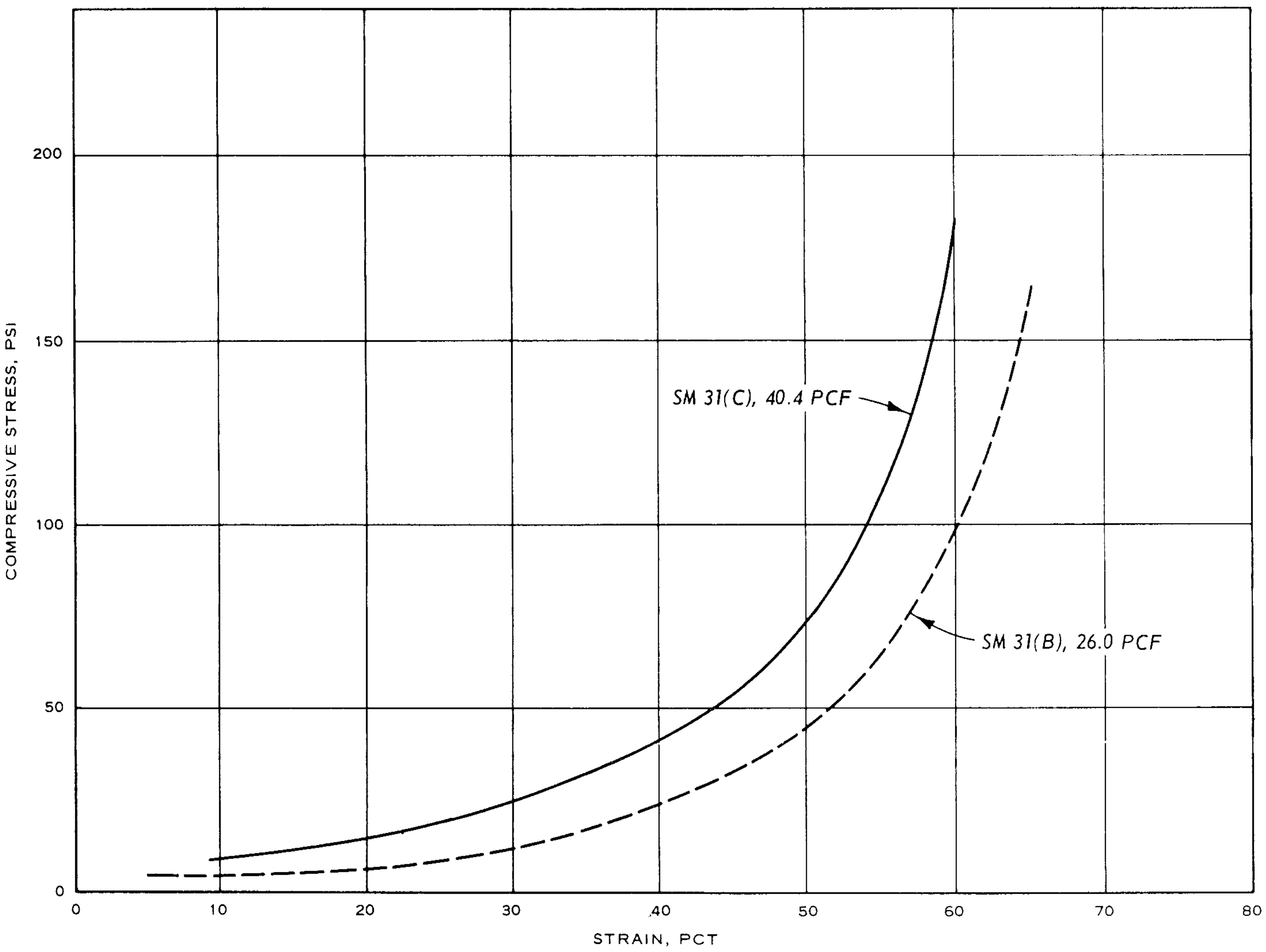

Figure 5.22 Stress-strain curves for bonded foamed rubber.

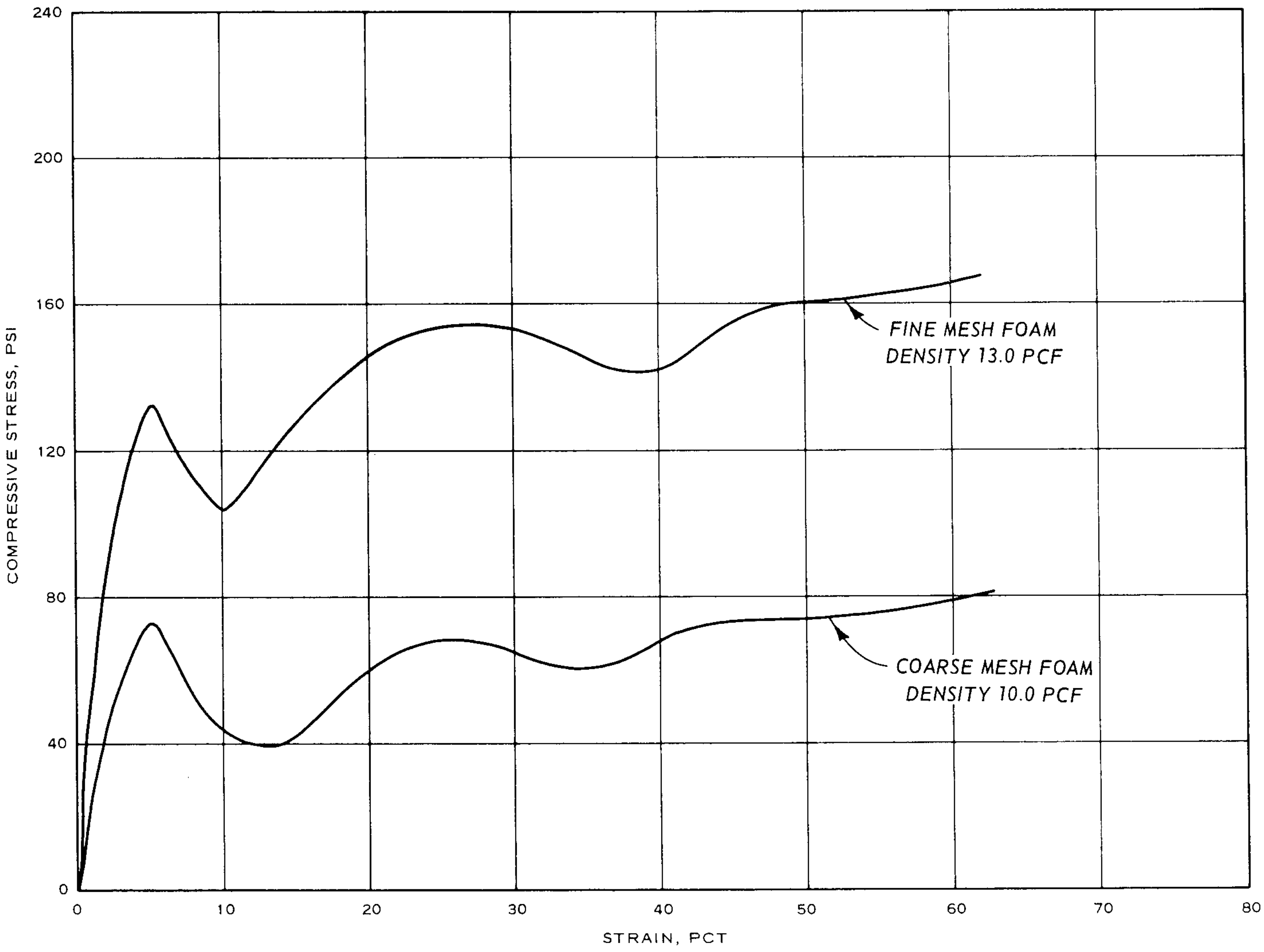

Figure 5.23 Stress-strain curves for foamed aluminum.

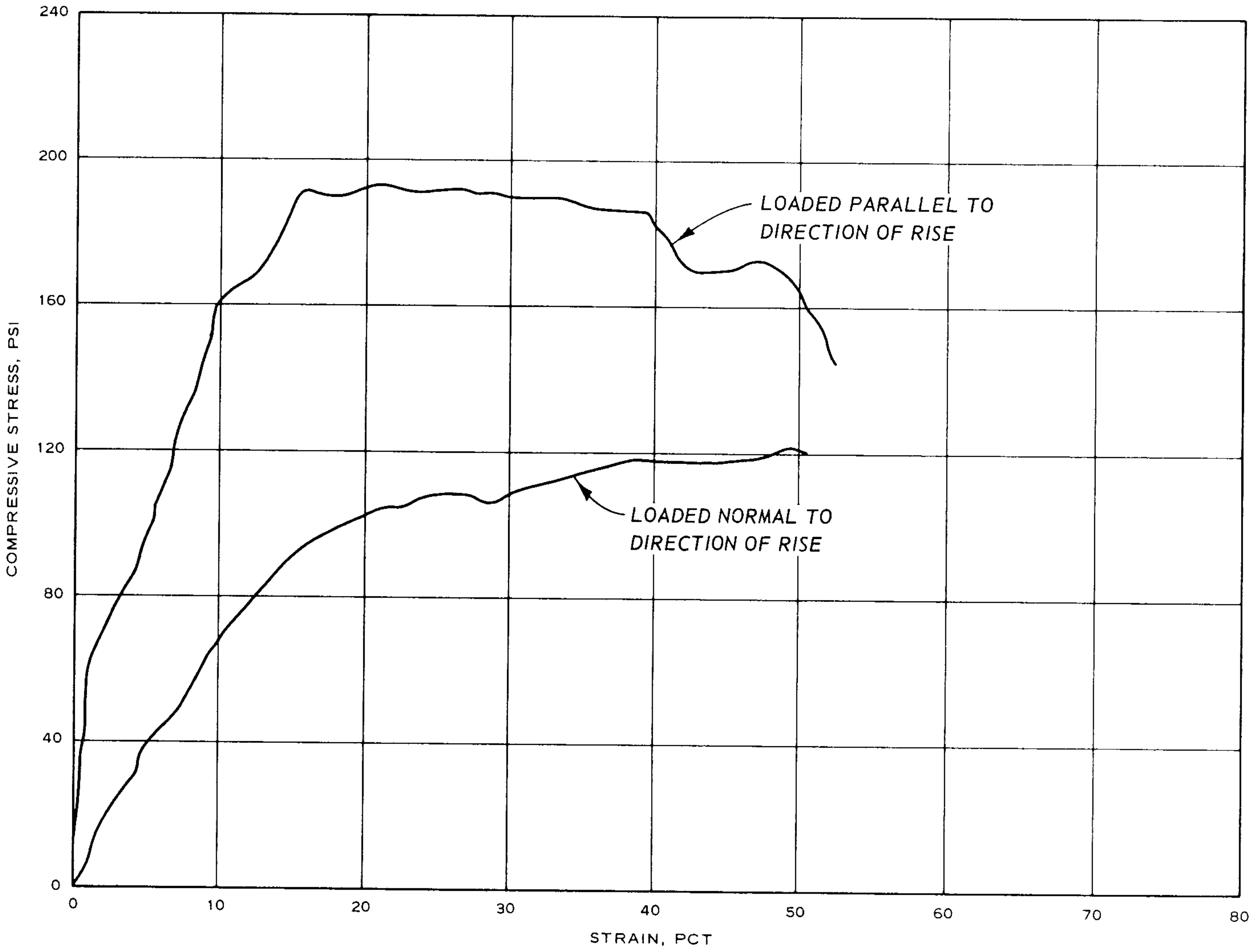

Figure 5.24 Stress-strain curves for foamed glass, density 9.1 pcf.

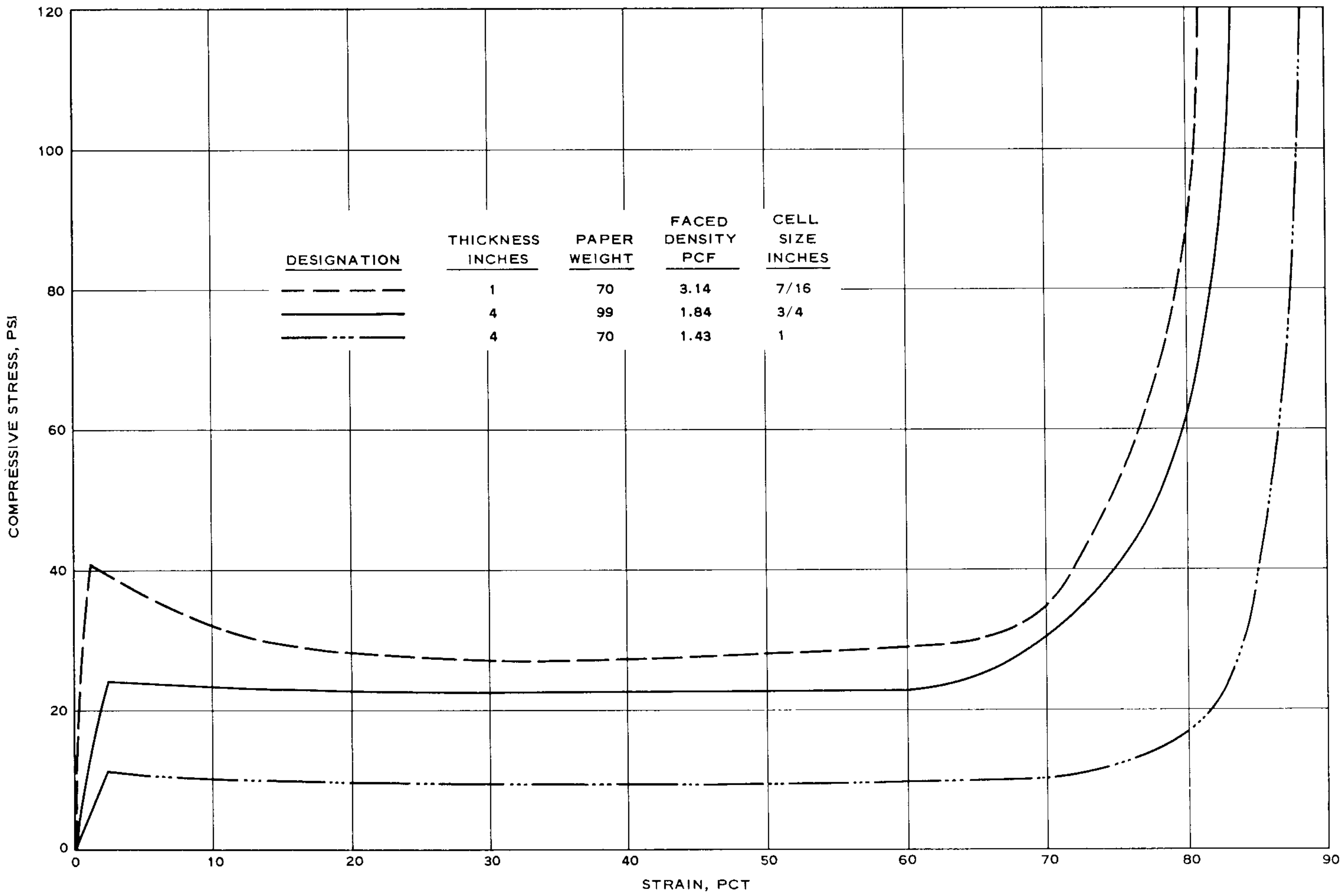

Figure 5.25 Stress-strain curves for paper honeycombs (untreated) (Reference 29).

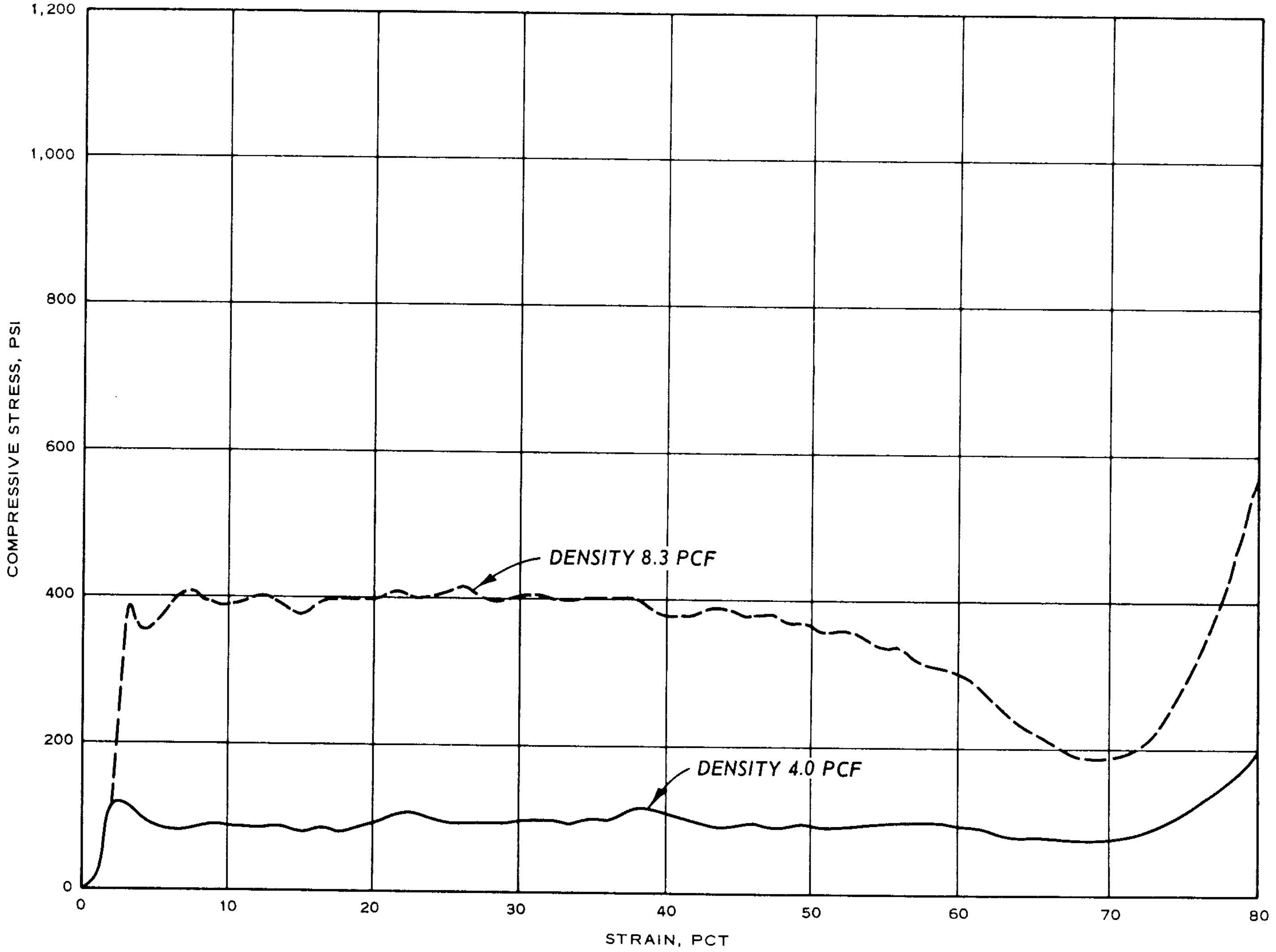

Figure 5.26 Stress-strain curves for aluminum honeycombs.

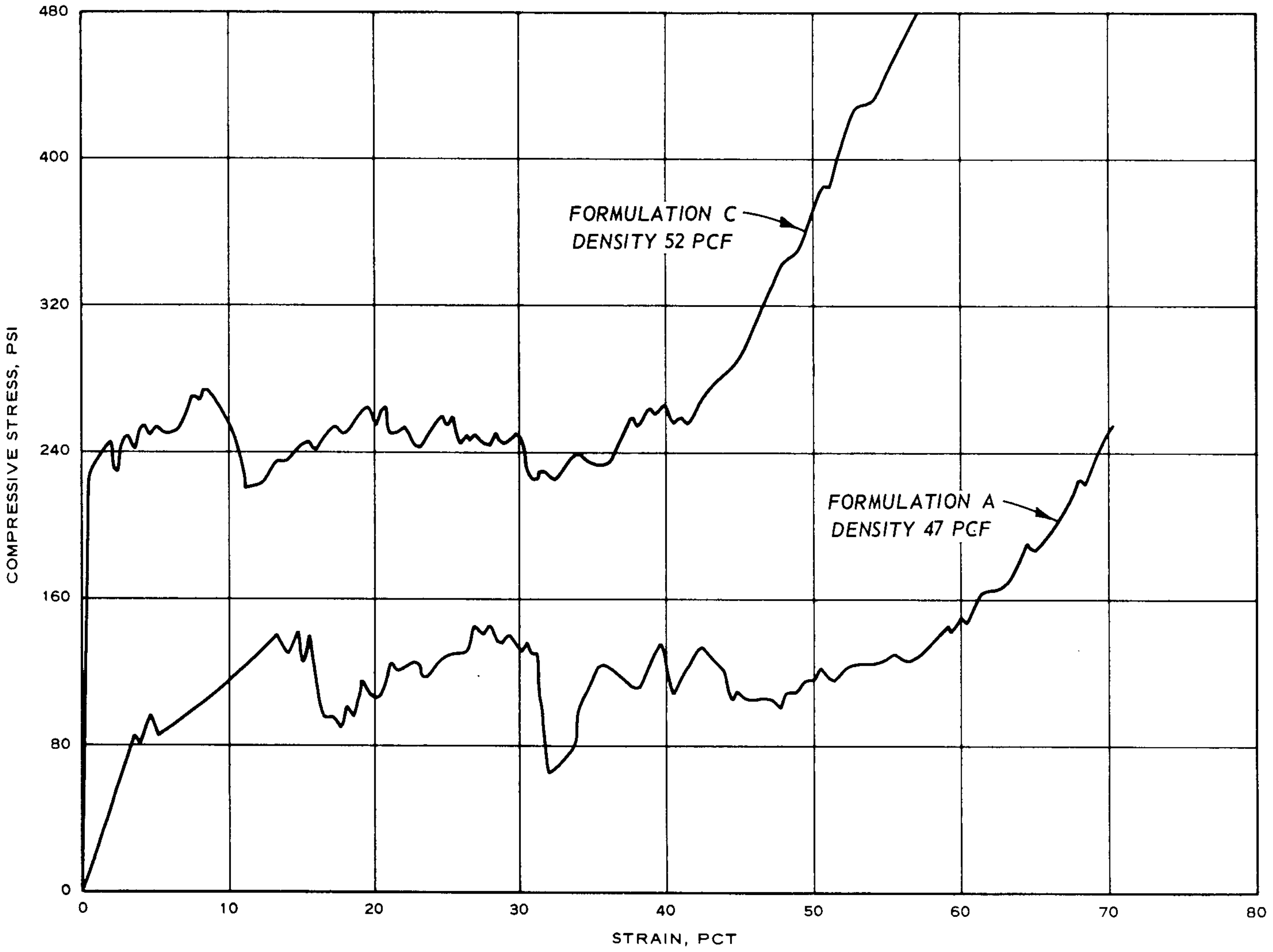

Figure 5.27 Stress-strain curves for foamed sulfur.

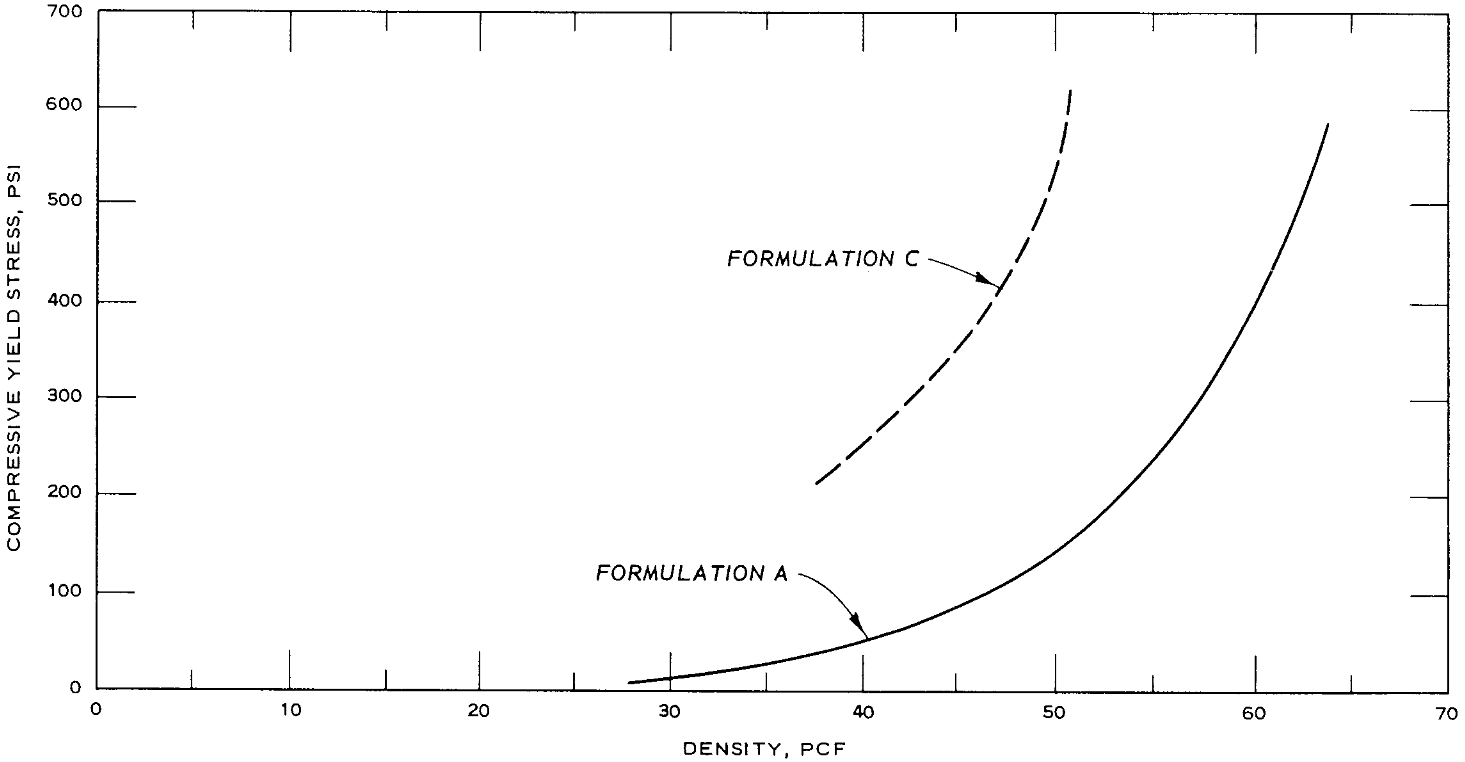

Figure 5.28 Compressive yield stress of foamed sulfur as a function of density.

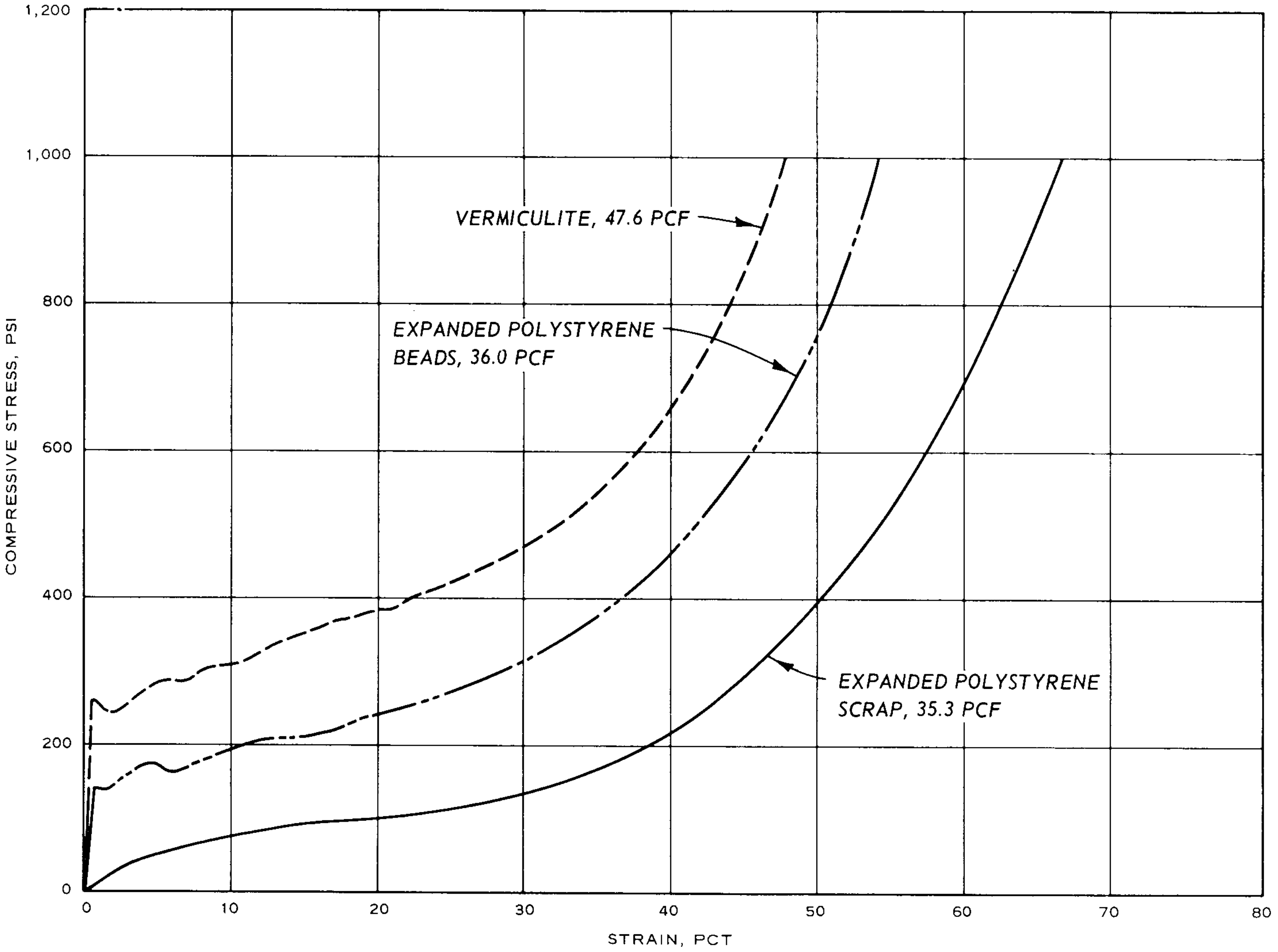

Figure 5.29 Stress-strain curves for low-density aggregate-type concretes.

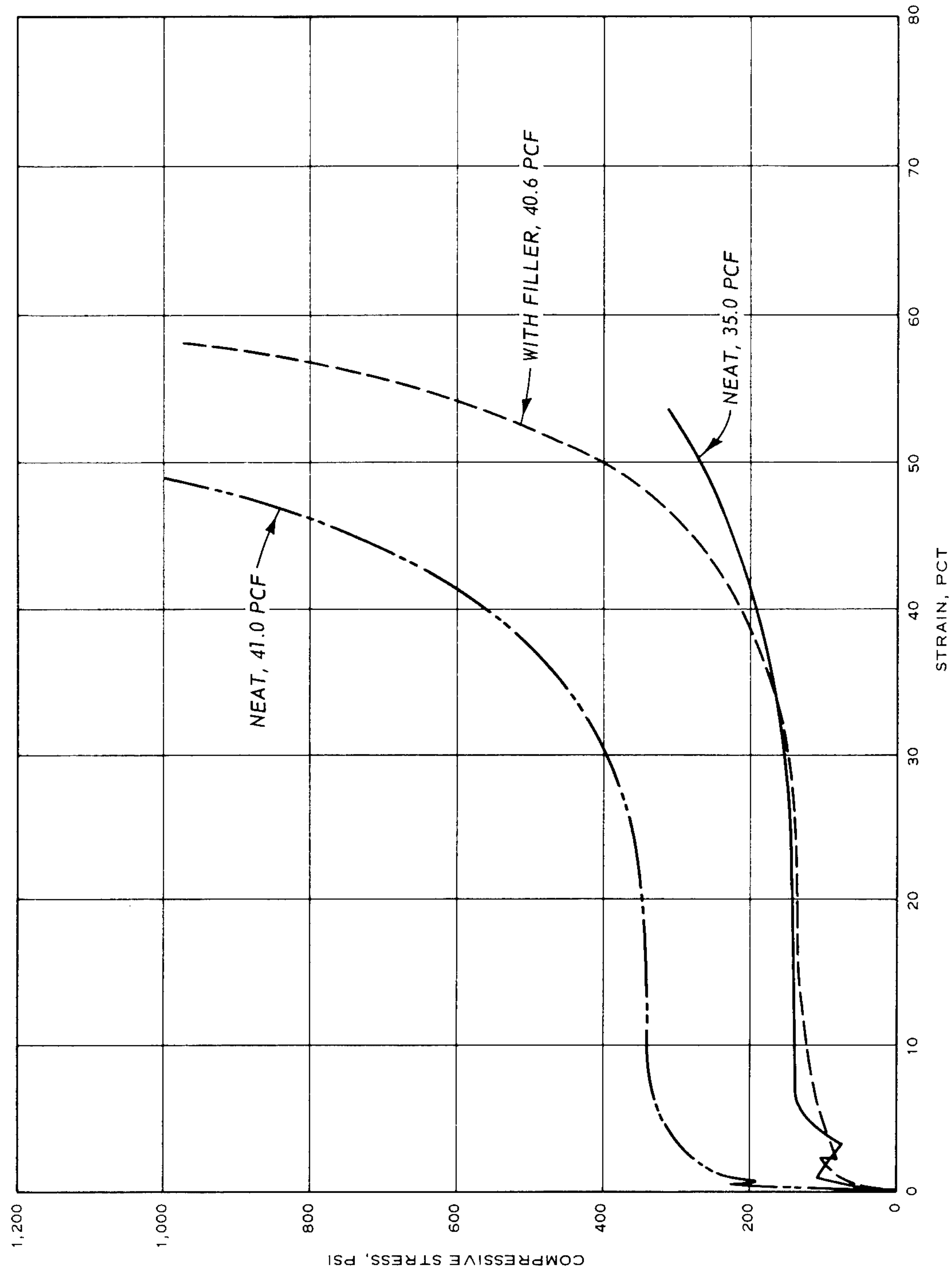

Figure 5.30 Stress-strain curves for low-density cellular-type concretes.

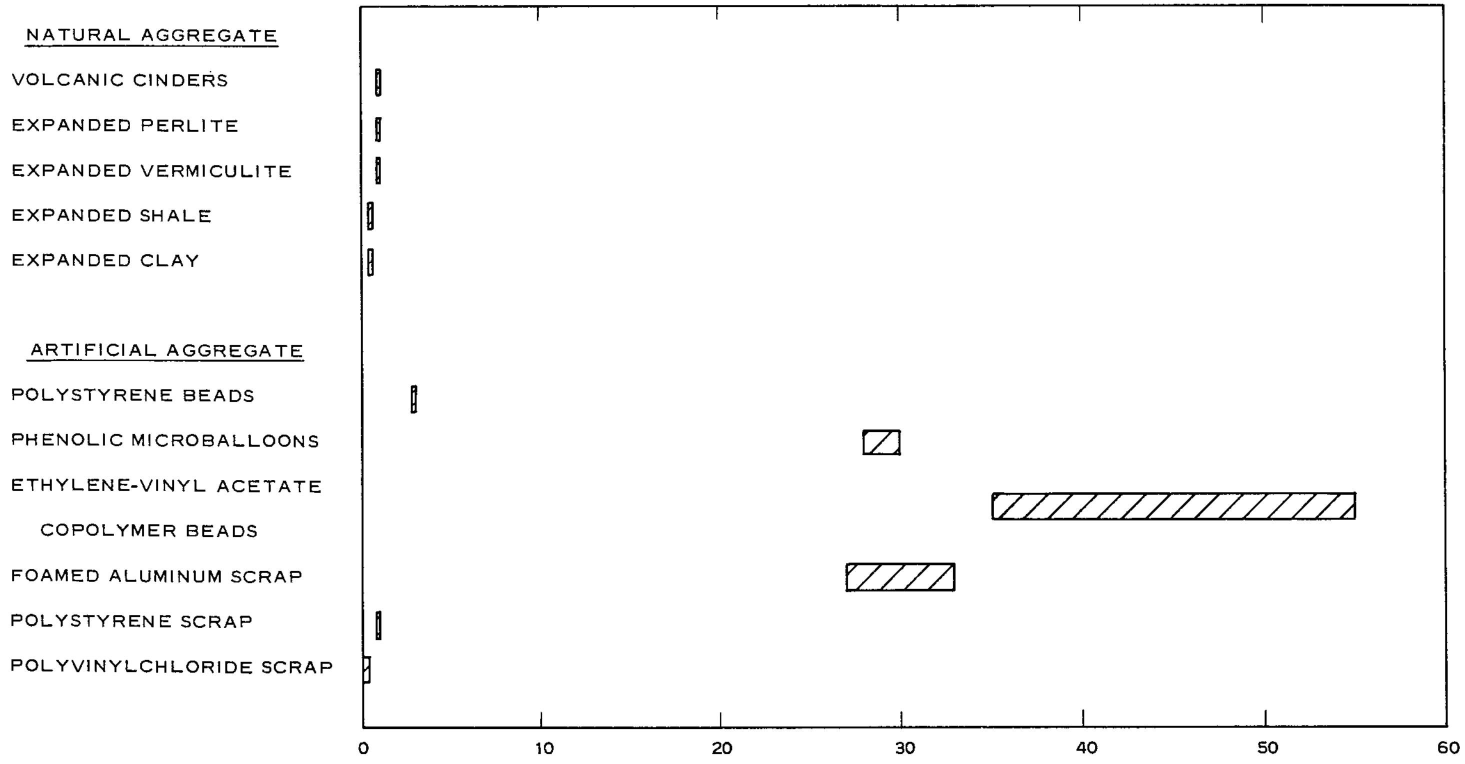

Figure 5.31 Relative cost per unit volume comparisons for granular materials.

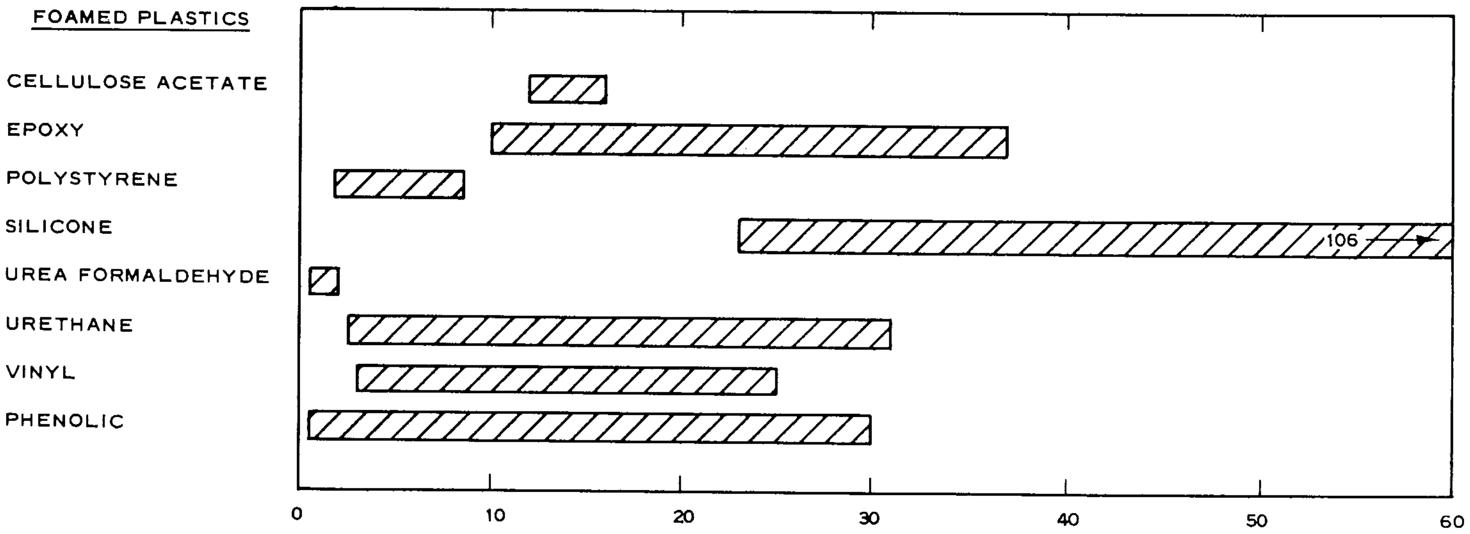

Figure 5.32 Relative cost per unit volume comparisons for foamed plastics.

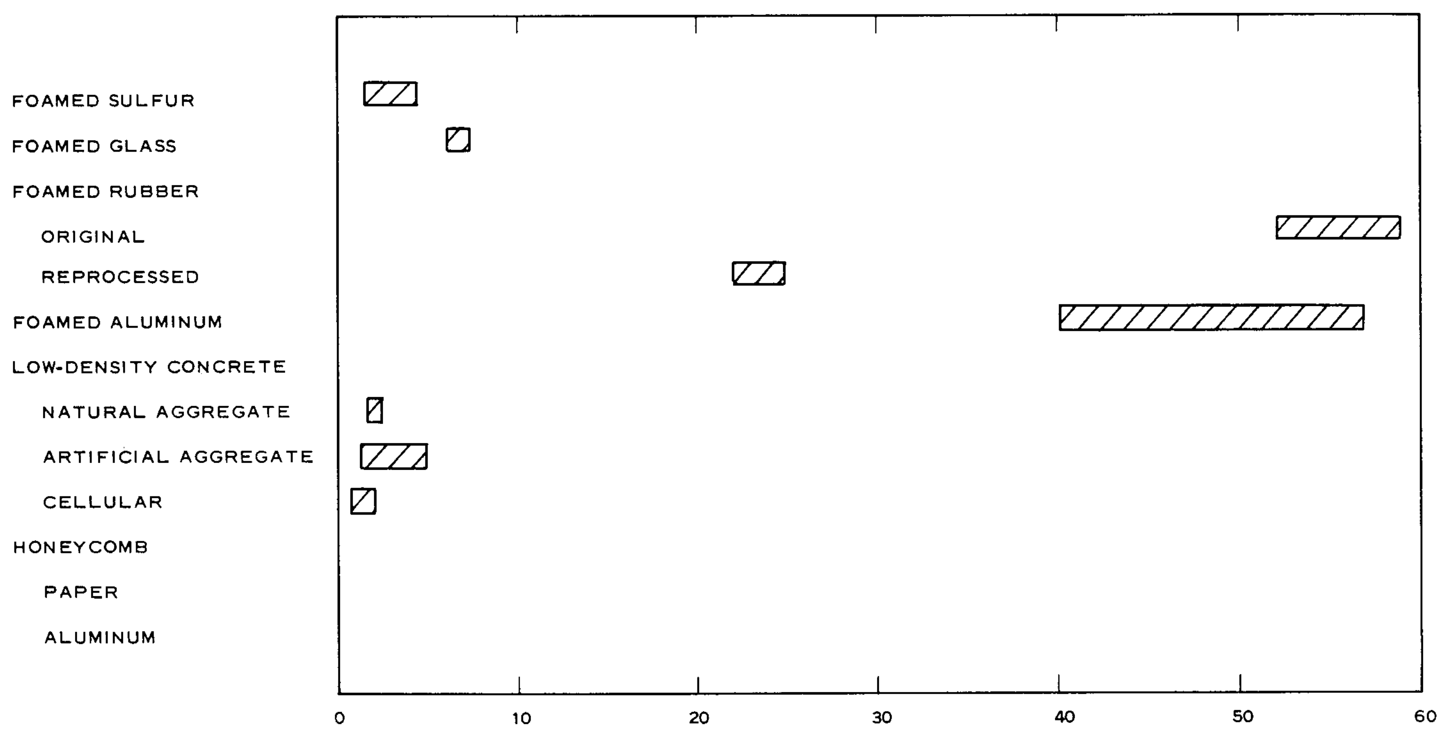

Figure 5.33 Relative cost per unit volume comparisons for other assorted backpacking materials.

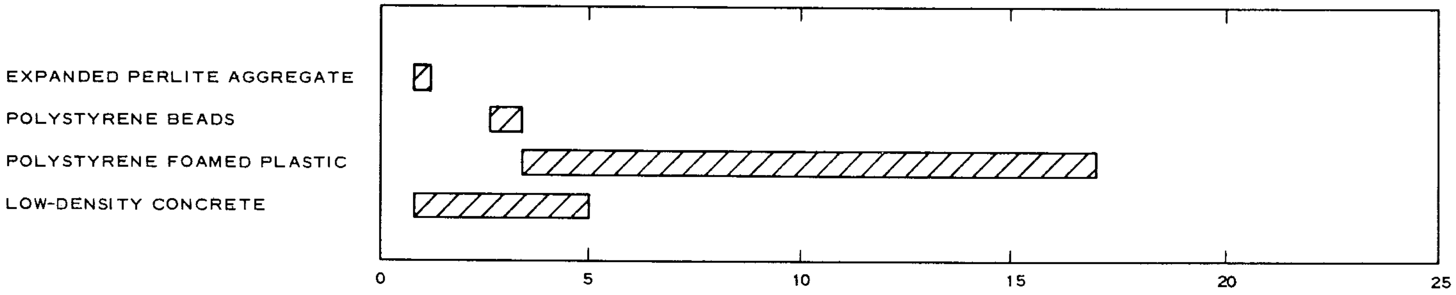

Figure 5.34 Relative cost per unit volume comparison for typical backpacking materials.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

Based on the results of the limited testing in this investigation and the information obtained from published reports and papers reviewed during the investigations, the following conclusions appear warranted:

1. The response of the backpacking and that of the liner are completely interdependent, and the design of one cannot be considered without the design of the other.

2. None of the materials investigated and/or reviewed in this work appear to satisfy all the design considerations set forth for a backpacking material.

3. The granular materials, flexible foamed plastics, and foamed rubbers investigated generally exhibit a plastoelastic behavior.

4. The foamed or cellular materials (which include rigid foamed plastics, metals, glass, sulfur), low-density concretes, and honeycombs investigated generally exhibit an elastoplastic behavior.

5. According to the design considerations set forth in this report, the elastoplastic behavior would be more desirable in a material than the plastoelastic behavior.

6. The solid-particle or grain portion of the materials reviewed generally contributes most of the strength to the backpacking system, while the voids encased in and around the solid particles provide the deformation capability.

7. Within the limitations of the materials' strength, most of the foamed elastoplastic materials and the honeycombs can be fabricated to provide a required deformation and crushing-stress level. The finished product may, however, be limited in size in order to assure product uniformity and/or accommodate the limitations of the fabricating process and/or equipment. The granular materials are somewhat limited as each material in question has its own unique strength properties and deformation capability which cannot be appreciably altered without changing the basic composition or form of the material.

8. Insufficient published information precludes a thorough understanding of the strain-rate sensitivity, multiple-shot loading capability, and water-absorption capacity under jobsite conditions for the materials reviewed. Generally, most of the materials investigated appear to be strain-rate sensitive and appear to be receptive to water infiltration when subjected to short-term, small static heads of water.

9. From a unit volume of materials cost standpoint for elastoplastic materials, the low-density concretes and foamed

sulfur are generally more economical than the foamed plastics, metals, rubbers, and glass investigated.

10. From a unit volume of materials cost standpoint, the expanded granular forms of naturally occurring materials (plastoelastic materials) investigated, while not possessing an ideal behavior response, are generally more economical than the elastoplastic materials investigated.

11. The ultimate selection of a backpacking material should depend upon the actual service conditions and the final cost of the in-place material.

6.2 RECOMMENDATIONS

Since the final selection of a suitable backpacking should be based on the service conditions that the backpacking will be subjected to, a number of suitable backpacking materials should be investigated and documented. None of the materials investigated and reviewed in this study appear to be entirely satisfactory as backpacking. The search for other existing materials and the modification of those materials already reviewed, plus the development of new materials, should be continued.

The elastoplastic behavior generally is more desirable in a backpacking material. As is evidenced from the artificial aggregate type of low-density concrete, the inclusion of a crushable aggregate in a suitable binder can produce this behavior. Investigations of suitable aggregates in various types of binders should lead to the development of some materials that are more satisfactory than those already in existence.

The application of existing methods of producing and fabricating elastoplastic materials such as foamed plastics, foamed metals, foamed glass, foamed sulfur, and low-density concretes to jobsite placement conditions should be investigated with possible modifications in the techniques and procedures being developed.

Suitable backpacking materials should be thoroughly investigated for strain-rate sensitivity, water-infiltration capacity, and multiple-shot loading capability.

The concept reviewed in this report is based on the premise that under a given set of jobsite conditions one material can be used as backpacking around a buried structure. It is wholly conceivable that perhaps a multimaterial system could be used in which each of the materials in the system could be designed to perform a certain function with the performance of the entire system ultimately satisfying the design considerations of a backpacking material. All the materials in the system need not be backpacking materials. This approach warrants some consideration as none of the materials investigated in this study, when acting singly, will satisfy all of the backpacking design considerations.

Sufficient data have not been accumulated to date to evaluate quantitatively the combined response of backpacking and the structure. Analytical models of the combined backpacking-liner response, supported by the measured response of backpacked models subjected to blast loading, are needed to alleviate this deficiency.

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The objective of this study was to review the existing theory and concepts pertaining to the use of backpacking materials around deeply buried protective structures and to provide a limited evaluation of a number of commercially available products in order to determine their suitability for use as backpacking. The basic theory, concepts, and applications pertaining to the use of backpacking around buried structures were compiled and are reviewed. Based on the premise that a one-shot, one-material backpacking system will be adequate for the requirements of a deeply buried structure, a number of backpacking design considerations were established. A cursory examination and review were given to 42 materials from 9 groups of materials to determine their practicality for use as backpacking. The groupings of materials by types include: granular materials, honeycombs, low-density concretes, flexible and rigid foamed plastics, and foamed rubber, glass, metal, and sulfur. None of the materials investigated and reviewed appear to satisfy all of the design considerations established for a backpacking material; however, this does not discount their being used as backpacking. The ultimate selection of a backpacking should depend on the actual service conditions the material will be subjected to, and these conditions may preclude some of the design considerations that the material in question cannot satisfy.

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