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SHOCK-ISOLATING BACKPACKING MATERIALS
A REVIEW OF THE STATE OF THE ART

by

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FOREWORD

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George C. Hoff*

SYNOPSIS

From a review of the types and effects of nuclear blast loading on buried structures, a basic design criteria for backpacking materials has been established and is reviewed along with the techniques used in determining the energy-absorbing characteristics of the backpacking materials. An example is developed to show how backpacking materials, when placed around buried structures, will absorb a portion of the applied shock energy thereby reducing the forces which reach the structure.

Various programs in the development of such materials as foamed plastics, honeycombs, insulating concretes, granular materials, and other similar materials which could be adequately used as backpacking are reviewed with limited data being presented.

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I. INTRODUCTION

The field of structure-medium interaction has long commanded the attention of individuals concerned with the design and construction of buried structures. With advances in the use of thermonuclear weapons, the difficulty in understanding structure-medium interactions and therefore the designing of buried structures has become further complicated by the introduction of complex ground motions and very high applied loads. The design of buried structures to resist these effects usually results in design loads which are so high that overconservative design would be extremely costly. On the other hand, catastrophic failure of the structure due to under-design cannot be tolerated.

The applied forces for which a blast-resistant 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 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. It is the purpose of this paper to review the state of the art of a technique that can be used for controlling the magnitude of the forces being applied to buried structures by blast loading, i.e., the use of backpacking materials for shock isolation of buried structures.

BACKGROUND

Approximately 50 percent of the fission energy of a low-altitude detonation (less than 100,000 feet) is utilized in the production of blast and shock[41].* The effective energy of the burst will be dependent upon the actual height of the explosion, as well as upon its energy yield, but the general phenomena are similar in all cases. Nearly all the shock energy appears as air blast which indirectly transmits energy to the ground. Some energy is also transmitted directly into the ground. Regardless of the mode of transmission, tremendous amounts of energy are introduced into the earth and, although some energy dissipation occurs through internal damping and the process of doing work on the media, considerable shock energy is still present at great distances from the explosion. The character and strength of the shock reaching a buried structure may be influenced by the stress-strain characteristics of the media the shock travels through[26]. In order to prevent excessive amounts of this shock energy from reaching the structure, a suitable method for dissipating the energy must be developed. This paper deals with the concept of using backpacking materials and reviews the types of materials currently under investigation for this purpose.

Recent Investigations

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, Engineering Research Associates, et al[9], in a report to the USA Corp of Engineers on Underground Explosion Test Programs suggested that

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* Raised numerals refer to similarly numbered items in the Literature Cited Appendix II.

"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 the 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."

In 1957, Vaile[42] reported on the beneficial use of a frangible backfill in isolating and protecting underground structures in operation PLUMBBOB from violent ground motions in their vicinity. During operation PLUMBBOB, vertical concrete pipes covered with concrete slabs were lined one layer thick on the sides and bottom with empty glass quart gin bottles. When compared to 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 experienced by 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 performed by Sevin, et al,[30,31] at the Armour Research Foundation (now the Illinois Institute of Technology Research Institute), various devices were employed on or about cylinders buried in silica sand in order to alleviate shock-induced motions of the cylinders. These devices consisted of, 1) wrapping the cylinders in flexible and rigid polyurethane foams; 2) the use of air voids between the media and cylinder; 3) the use of pre-expanded polystyrene beads as a crushable backfill aggregate and, 4) the use of sand of varying densities as backfill aggregate separated from the over-all bed by a stove pipe. The conclusions reached were that polyester urethane foams placed around a cylinder and other materials functioning as a loose backfill aggregate were effective in attenuating the response of the isolated structures

Da Deppo and Werner[5], in a study on the influence of mechanical shielding on the response of buried cylinders, introduced a crushable layer directly over the buried cylinder. The use of this crushable material greatly reduced the magnitudes of the loads reaching the cylinder.

Fowles and Curran[10], in presenting theoretical descriptions of the propagation of a pressure pulse in a potential backpacking material, suggest 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, Newmark and Merritt[26] state that the current design concept for protective linings in competent rock includes the provision for a highly deformable material between the face of the rock and the lining:

> "It would appear that the magnitude of . . . forces (generated by small impacts) reaching the lining could be significantly reduced if a crushable material is introduced between the face of the rock and the lining[26]."

Smith and Thompson[36], suggest that the shock energy reaching a buried structure in rock can be partially dissipated by: 1) a reflection of energy, and 2) by energy absorption. They suggest that these requirements be met 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 which occurs will cause some energy to be reflected. If the low-shock impedance material is also very deformable under applied loads, it will absorb the energy present in the form of ground motions, thereby meeting the two requirements.

Design Criteria

A review of the investigations cited above and other similar projects provides an insight as to what is necessary in designing a backpacking system for shock-isolation 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. If possessing these characteristics, the material should dissipate a portion of the shock energy, thereby reducing the magnitudes of the forces reaching the structure and should accommodate the deformations of the cavity in which the structure has been placed. Due to the large relative costs of construction versus design over-pressures[3] the scope of interest of this paper will be restricted to design over-pressures less than 1000 psi; that is, the magnitude of stress transmitted to the structure through the backpacking material will be less than 1000 psi. Assuming single burst loading where closure of the cavity is imminent, deformations of the backfill to accommodate this closure should be approximately 50%. In other cases, it may be considerably less.

II. THEORY

Pressure-volume, Stress-strain Relationships

The majority of the materials investigated both in the past and at present 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 single-rigid locking solid (Fig. 1) and an elastic-rigid locking solid (Fig. 2) respectively.[10]

Consider first the case of a simple-rigid locking solid (Fig. 1). The original volume is designated Vo. Under a very small applied pressure, the specific volume decreases to V_1 at no appreciable increase in the pressure. At V_1, the material locks with no further decrease in volume occurring with additional increases in the pressure.

In the case of the elastic-rigid locking solid (Fig. 2), the pressure-volume curve is very similar to that of the simple-rigid locking curve but with the addition of an elastic region containing a definite yield point. As in the previous case, the initial specific volume is represented by Vo. Under the application of pressure the material behaves as an isotropic elastic solid until Pe, the elastic yield pressure is reached. Beyond that pressure, the material behaves like a simple-rigid locking solid.

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 simple-rigid and elastic-rigid locking solids subjected to one dimensional compression (Fig. 3). To indicate more clearly the behavior of real materials, the locking portion of the curves has been shown as an inclined line representing the elastic behavior of the solids composing the materials under consideration. With the addition of this elastic portion, the simple-rigid and elastic-rigid locking solids will hereafter be referred to as plasto-elastic and elasto-plastic materials respectively. This conversion to a stress-strain relationship provides a convenient tool for evaluating the energy dissipating capability of the materials.

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[8]. The product of the strain and the unit force results in the amount of energy absorbed by the material:

$$E_n = \bar{\sigma} \times \epsilon = \text{area under the stress-strain curve (Fig. 4)} \qquad (1)$$

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

$$E_n = \int_0^{\epsilon} \sigma \cdot d\epsilon \qquad (2)$$

Before proceeding, a distinction should be made between the terms, "energy absorbed" and "energy dissipated." Figure 5 represents a typical stress-strain curve for a material possessing elasto-plastic 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[8], or,

$$\text{Absorbed Energy} = \text{Dissipated Energy} + \text{Rebound Energy} \qquad (3)$$

Much work has been done in the past both by industry and government in the development of energy-dissipating theories and mechanisms. It is not my purpose here to make a thorough survey of all the literature on the absorption of energy but rather to discuss the use of backpacking materials for dissipating shock energy reaching buried structures. An annotated bibliography of literature pertaining to the absorption of impact energy has been prepared by Ali and Benson[2], which, although concerned with the problem of absorption of impact energy in the air drop of supplies and equipment, reviews the theory and design of energy-absorbing systems plus the energy-absorbing materials which may be available. This bibliography may be referred to for a more comprehensive review of the energy-absorption concept.

From the energy relationships described previously, it becomes obvious from the shape of the stress-strain curve that elasto-plastic materials are more efficient energy absorbers than the plasto-elastic materials. Both materials are under consideration for use as backpacking, however, because the plasto-elastic materials may be more economical and thus more attractive when large volumes are necessary.

Stress Transfer

When the closure of a cavity containing a backpacked liner is uniform, the deformation of the backpacking will also be uniform, and hence, 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 non-uniform, the liner will tend to deform into an oval or elliptical shape as shown in Fig. 6.

Newmark[25], in discussing the factors to be considered in designing blast and ground shock-resistant structures, approached this problem by permitting the lining to deform by such an amount so as to develop in the backpacking appropriate resisting stresses against the deformation. The lining must, in this case, 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, Newmark[25] allowed a and b (Fig. 6) to represent the displacement of the cavity walls. However, because of the deformations, y, of the liner itself, the net change in thickness of the backpacking at the sides is $b - y$ and $a + y$. By assuming a general situation of load-deformation for an elasto-plastic material (Fig. 7), it can be readily seen that the magnitude of the net differential pressure between points b and a, assuming the lining does not deform, is much greater than the net differential pressure between points $b - y$ and $a + y$ when the lining does deform. If the loads at deformations $b - y$ and $a + y$ are expressed as $q + p_1$ and $q - p_1$, respectively, it can then be said that the average of these pressures is the uniform component of load, q, and that the difference from the average is p_1, the inward or outward component of load. It is this component of load, p_1, which tends to produce the elliptical or oval deformation of the lining. As can be seen from the ideal curve in Fig. 7, the larger the net differential pressure is, the greater p_1 is. When p_1 is large, the deformations of the lining are large. When lining deformations are large, the backpacking is compressed more, thus causing the pressure differential to become smaller, which in turn reduces p_1 and thus the deformations of the lining and so on 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 relationship for plasto-elastic materials but with a little more difficulty as it is relatively impossible for a lining interacting with the progressively increasing stress-strain relationship of a plasto-elastic material to develop a resistance characterized by a nearly uniform compression on all sides.

Thickness Determinations

In general, the backpacking is most effective when designed to have an energy absorbing capacity equal to that of the core of material removed to form the cavity[25]. For a plane wave of stress, assuming average deformations of the cavity, the total strain energy, both elastic and plastic, which would have existed in the core of material that was removed can be evaluated and equated to the relationship shown in equation (2). By trial and error procedures, $\bar{\sigma}$, the average plastic stress in the backpacking and, ϵ, the plastic strain in the packing, can be evaluated.[17] The total plastic strain plus volume allowances for the solid elastic particles of the backpacking form the basis for determining the thickness, t_f, of the backpacking. When the cavity is in rock, the bulking phenomena* and the kinetic energy of spall projectiles must also be considered in the thickness determination.[25]

* 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.[25]

III. MATERIALS

The two ideal stress-strain relationships shown in Fig. 3 define the properties of a variety of materials. Fig. 8 shows the relationship between the ideal and typical stress-strain curves for both types of materials.

The typical curve shown in Fig. 8a represents the stress-strain relationship for materials that do not possess a definite yield point (plasto-elastic) but are still very compressible, either elastically or inelastically, or both. Granular materials are a representative material for this type of curve. Some plastics and rubbers also possess these characteristics. However, the plasto-elastic materials discussed in this paper will be primarily the granular materials.

Fig. 8b represents the typical stress-strain curve for elasto-plastic materials compared to the ideal curve. Insulating concretes and plastic foams are good representatives of this class of materials, although some granular and other materials also exhibit this type of behavior.

Cost:

In the following discussion, no attempt will be made to compare any of the materials on the basis of actual cost in place, but for general information purposes, it may be mentioned that granular materials are, with few exceptions, the least expensive materials. The insulating concretes, which cost more in place than the granular materials, are less expensive than the most economical foamed plastics and honeycombs in place by a factor of 10 or more.

Such factors as the actual material used, degree and amount of isolation required, the environment in which the structure is located, construction techniques, and other related factors, while all somewhat interdependent, contribute in varying degrees to the total in-place-cost of the material, thus making any cost comparison except a general one almost impossible. The cost of the backpacking system and, hence, its feasibility, should be evaluated for each proposed structure considering the known environment, assumed loading, and desired response that will be unique to that structure.

Plasto-Elastic Materials

Granular Materials. Numerous studies have been made to define the energy-absorbing mechanisms of granular materials subjected to applied states of stress. The bulk of these studies, however, have been concerned with granular materials of considerable strength that were subjected to stresses well in excess of our present level of interest. Excellent summaries of the state of the art pertaining to the mechanisms and behavior of these granular materials have been compiled by Deresiewicz[7] and Whitman[43].

The general stress-strain relationship in granular materials is very complicated and is to a large extent dependent on the magnitude of the applied pressure. Hendron, et al[12], in reporting on the energy-absorption capacity of granular cohesionless materials in one-dimensional compression 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, adequately illustrates (Fig. 9) the phenomena necessary for backpacking using granular materials.

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 occur during the particle rearrangement, thus resulting in a concave upward curve for the same region[20]. The absorbed energy in both cases is 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 over-all behavior is essentially non-linear 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 them .lves. Most of the energy dissipated here in forming new surface and consolidating the particles is nonrecoverable.

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

As can be seen from the upper curve in Fig. 9, the average stress required for compaction depends on many things 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 which composes the grain. Because our interest is in materials whose stress level at approximately 50% strain is less than 1000 psi, we will be concerned mainly with Region 1 and perhaps the lower portions of Region 2.

Normally the strength of the grains of competent naturally occurring material are too great to provide the large deformations required before

1000-psi applied pressure is reached. Some naturally occurring grains, however, do possess this deformation capability because of the very friable, vesicular nature of the grain. Klotz[20] reported on one such material, volcanic cinders, in an investigation of various materials for use as backpacking for Operation NOUGAT, Shot HARDHAT. Other naturally occurring materials can be altered by various mechanical and thermal methods to produce grains of a composition suitable for shock isolation purposes. Such materials as expanded clay[15], expanded shale, expanded slag, coke, coal cinders[20], vermiculite[15,27,36], and perlite[15,27], have been investigated for their shock-dissipating characteristics by numerous investigators with some of the results of their static tests being shown in Fig. 10a.

Artificial grains can also be used for shock-isolation purposes. The waste products of various plastic-foam manufacturing processes often can be adapted for use as granular material. The industrial waste as wellas artificial grains manufactured in the form of chips or aggregate, often provides adequate shock-dissipating characteristics. Such artificial materials (Fig. 10b) as phenolic micro-balloons[10,15], expanded polystyrene beads[15,30], plastic foam chips[15,20], foamed metallic waste, and foamed rubber waste[15] have been evaluated and found adequate. There are many waste materials which could prove adequate, but because waste is not deliberately manufactured, availability and perhaps cost would probably be limiting features.

Foamed Materials. Many foamed materials do not possess a definite yield point but begin to deform with the application of very small pressures. The resulting stress-strain curve is progressively locking and can be assumed to represent a plasto-elastic material. Examples of this type of foamed material are shown in Fig. 11[1].

Elasto-Plastic Materials

Many investigations into the energy dissipating characteristics of various elasto-plastic materials have been conducted over the years in connection with the packaging industry and the Quartermaster Corps' requirements for air-drop cushioning[1,2,28,38]. From these investigations emerged a family of foamed plastics and honeycombs whose stress-strain relationship approximate that of the ideal elastic-rigid locking solid. These materials can be fabricated so that the binder will furnish the crushing stress level desired with the fractional volume of voids or pores in the material being controlled so as to obtain the necessary deformations. This is not the final answer, however. A good many of the foamed plastics and honeycombs are very expensive and are relatively difficult to handle and place in sufficient quantities and in adverse environments which may be dictated by the design and location of a buried structure. These problems, in general, fostered the need for a relatively inexpensive construction material which would serve the same purpose. Research at the University of Illinois[20], University of Texas[33,35,36], and the Waterways Experiment Station[15], has shown that insulating concretes, i.e., concretes having oven-dry density of less than 50 pfc, while not as efficient as foamed plastics and honeycombs in some respects, will provide the desired shock-isolation characteristics. The discussion in the next few paragraphs will be restricted to these three types of materials, i.e., foamed plastics, honeycombs, and insulating concretes, as it is the author's belief that they are most representative of what can at the present time be used most effectively as an elasto-plastic material for shock isolation.

Plastic Foams. Not all plastic foams possess an elasto-plastic stress-strain relationship. As shown previously, the "flexible" plastic foams often produce a plasto-elastic stress-strain relationship as shown in Fig. 11. "Rigid" plastic foams generally produce the elasto-plastic relationship. Both types transfer stress and dissipate energy, but, as shown before, the elasto-plastic material is more efficient in both respects.

A variety of rigid foamed plastics are available and suitable for shock-isolation purposes, but, more often than not, they are extremely expensive. The rigid polyurethane foam is perhaps the most widely investigated[15,20,32,35,40], and used[10,23,30], for this purpose. Fig. 12 shows a number of stress-strain curves for a rigid polyurethane foam. Despite its high cost, rigid polyurethane is still attractive as it is available in most areas, is fairly homogeneous and isotropic when formulated properly; it possesses the desired stress-strain relationship (Fig. 12); it possesses the capability of being fabricated in the field and, if closed cell, is somewhat nonsusceptible to ground-water infiltration which would reduce its energy-dissipating potential.

Other types of foam which have been reported as suitable energy dissipators are polystyrene[15,22], and polyvinyl chloride[10,15]. These two materials are also very expensive and are normally available only in relatively small pieces as compared to the needs of isolating a structure. The cost of assembling and fitting the small pieces around a structure would be very great.

Research into and development of the capability of casting large volumes of foamed plastics around tunnel liners is currently being undertaken and, if successful, will undoubtedly influence their in-place-cost so as to make them more attractive for shock isolation purposes.

Honeycombs. The use of prefabricated honeycombs has proved an effective means of energy dissipation and stress transfer. Honeycombs have the advantage of being very isotropic if designed properly so that the maximum stress in the packing can always be limited. They can also be largely impervious to ground-water infiltration. The main disadvantage honeycombs have is the large costs that will be incurred in the placing of the material around the structure.

There are two basic types of honeycombs: paper and metallic honeycombs. Paper honeycombs are used primarily at stress levels less than 100 psi[1,8,16,19,39] (Fig. 13), while the metallic honeycombs are more effective at stresses in excess of 100 psi[1,11,13,21,29,38] (Fig. 14). Because of the nature of the composition of the honeycombs, it is doubtful if a good bond between the honeycomb and the structure will be obtained. Manufacturers[11], however, claim that an excellent forming and bond can be obtained with metallic honeycombs.

Insulating Concretes. Insulating concretes are best defined as concretes made with portland cement, water, air, and possible aggregate additions to form a hardened material which will have an oven-dry density of 50 pcf or less.

As in the case of the foamed plastics, the hardened matrix provides the crushing stress level while the voids necessary for deformation are provided by the air and in part by the aggregate. The strength of the hardened portland-cement paste can be readily controlled but the deformations present some problems. If an aggregate is used, it must be very weak and friable. Regardless of its strength, however, it still contributes somewhat to the over-all strength of the hardened mass. Experience has shown that the addition of too much aggregate in order to obtain more deformation, adversely affects the workability of the concrete, thus making it very difficult to handle and place. The solution is that most insulating concretes, such as vermiculite[4,15,33,35,36], and perlite[20,27] concrete, require as much as 20 to 30 percent entrained air in order to become suitable shock dissipators. Cellular concrete[14,15,20], which may or may not contain a fine sand or filler, can often be found with air contents as high as 75% 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 voids, upon becoming filled with fluid, lose their effectiveness for shock dissipation as they then transmit shock loads through the fluid. Tests[15,36], have shown 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. It is the author's opinion that this absorption problem is not insurmountable and could be remedied, at least in part, by the use of such methods as chemical "waterproofers," sandwich construction, grout curtains, and well-point systems.

Typical stress-strain curves for three of the most popular insulating concretes are shown in Fig. 15, along with a curve for concrete made with a plastic aggregate (expanded polystyrene beads)[15]. All of these concretes are relatively inexpensive when compared to the cost of the foamed plastics and honeycombs and can be fabricated and placed in most environments using conventional construction equipment.

Other Materials

As evidenced by the introduction of a plastic aggregate into a portland-cement matrix shown in Fig. 16, it becomes obvious that many different types of materials systems possessing an elasto-plastic stress-strain relationship can be developed simply by the inclusion of air or a collapsible aggregate into a suitable binder. Various types of ultra-lightweight concretes, plastics with aggregate inclusions, and such foamed binders as epoxy[15], asphalt, gypsum, sulphur[6,21,37], and various chemical compounds all possess possibilities as shock dissipators.

IV. SUMMARY

The behavior of a buried structure subjected to blast loading must be evaluated on the basis of the loads reaching the structure. Research has shown that the use of a properly designed backpacking material placed around the structure dissipates a portion of the shock energy present in the free field, thereby reducing the magnitude of the forces reaching the structure. The response ofthe backpacking then and that of the structure are completely interdependent and the design of one cannot be considered without the design of the other.

Unfortunately, sufficient data have not been accumulated to date to evaluate quantitatively the combined response. Both laboratory and field programs have been initiated to remedy this deficiency. Analytical models are being developed at the Illinois Institute of Technology in an attempt to describe the response of backfilled structures in soil. Other work is also being conducted to measure the response of backpacked models subjected to blast loading.

Each of the types and systems of materials reviewed undoubtedly has ay unique problems associated with its use as backpacking. However, the plementing of adequate research and development of the materials in question would probably solve the majority of these problems. An excellent ample of this is the study currently being conducted at the Southwest search Institute[6,24,37] on the feasibility of foaming bulk sulphur for se as a shock-isolation material around buried structures. A relatively w-cost foamed sulphur possessing an elasto-plastic stress-strain curve, fig. 16), plus some other desirable features, has been developed and the easibility of its large scale application is being studied.

This type of laboratory research coordinated with such field programs as Operation NOUGAT, Shot HARDHAT,[23] Operation HARDTACK,[34] and other related programs will, together with the development of suitable shock-isolation backpacking materials, probably result in less vulnerable buried structures at reduced costs.

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APPENDIX I: NOTATIONS

a, b = displacements of cavity walls

E_n = energy absorption per unit volume of material

Pl = varying component of packing pressure on liner

P_e = pressure at elastic yield-point of the material

P_o = original pressure

P_l = pressure at the locking state of the material

q = uniform component of packing pressure on liner

r = radius

t_f = thickness of backpacking

V_e = volume of material at pressure P_e

V_o = original volume

V_l = volume of material in the locking state

y = deformation of liner

ϵ, ϵ_1, ϵ_2 = strain

σ = stress

$\bar{\sigma}$ = average stress

APPENDIX II: LITERATURE CITED

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ERRATA

Due to additions to the literature cited after Figures 1 through 16 had been completed, the raised reference numerals in the following figures corresponding to similarly numbered items in the literature cited are in error and should be changed to correspond to those numerals shown below:

Existing Number	New Number
1	1
4	4
7	8
10	12
13	15
17	20
18	21
21	24
22	25
24	27
33	39

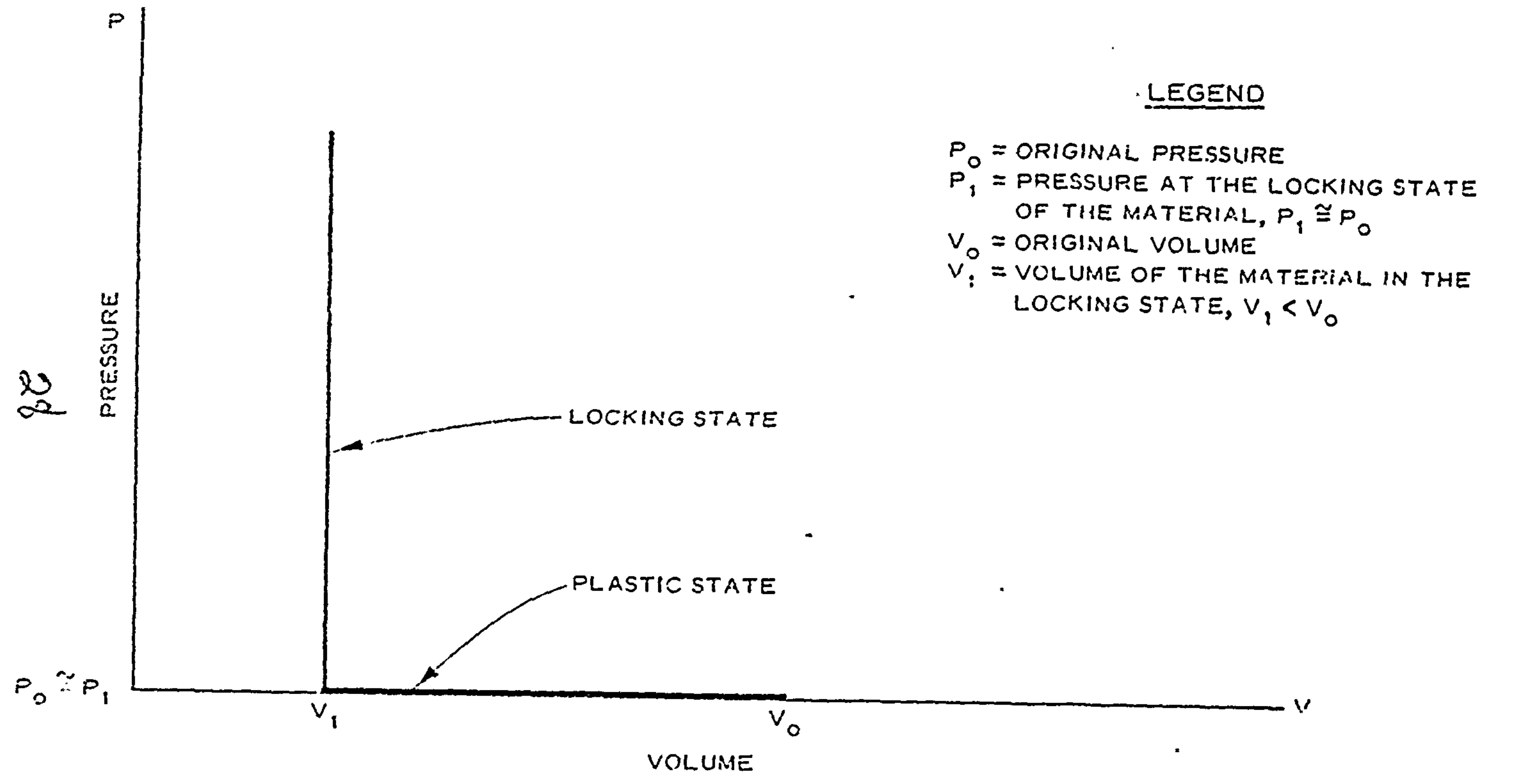

Fig. 1. Pressure-volume relation for a simple-rigid locking solid

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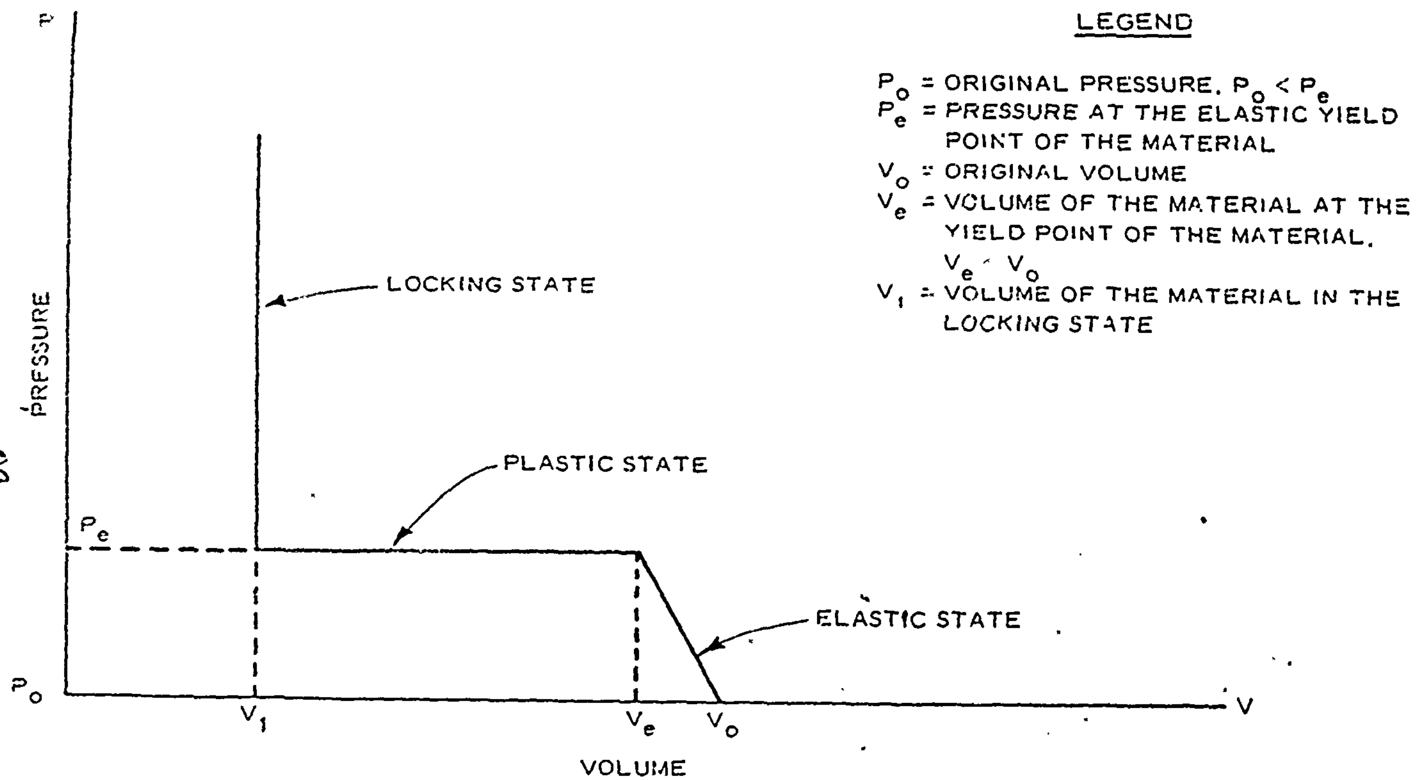
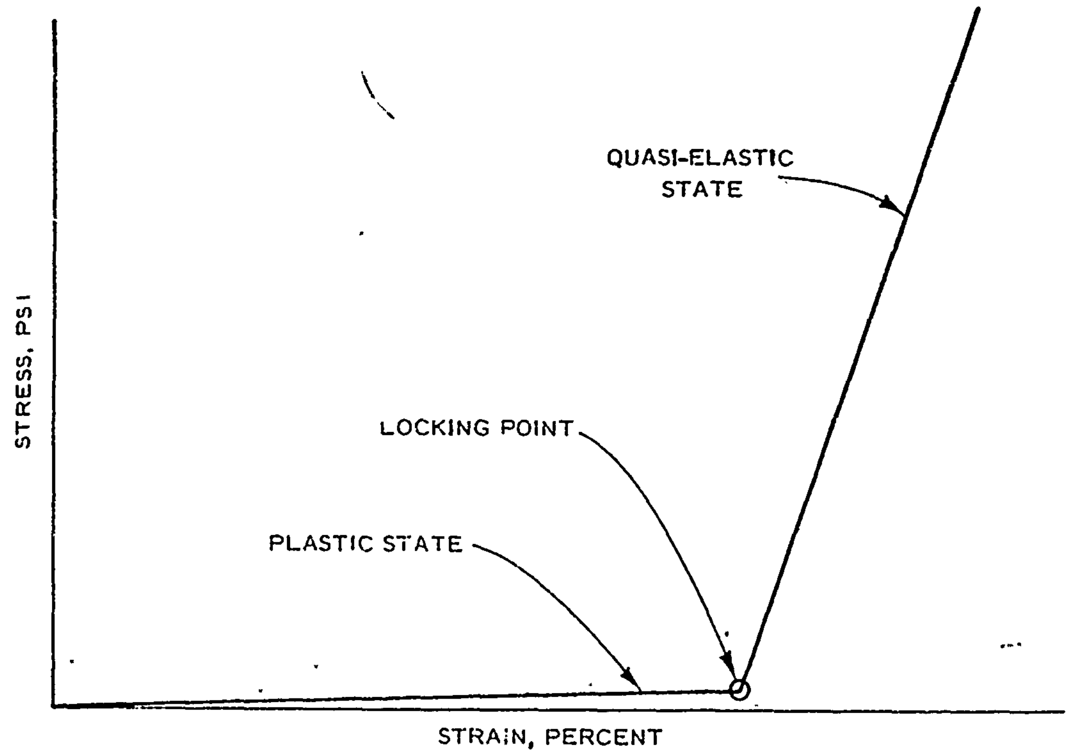
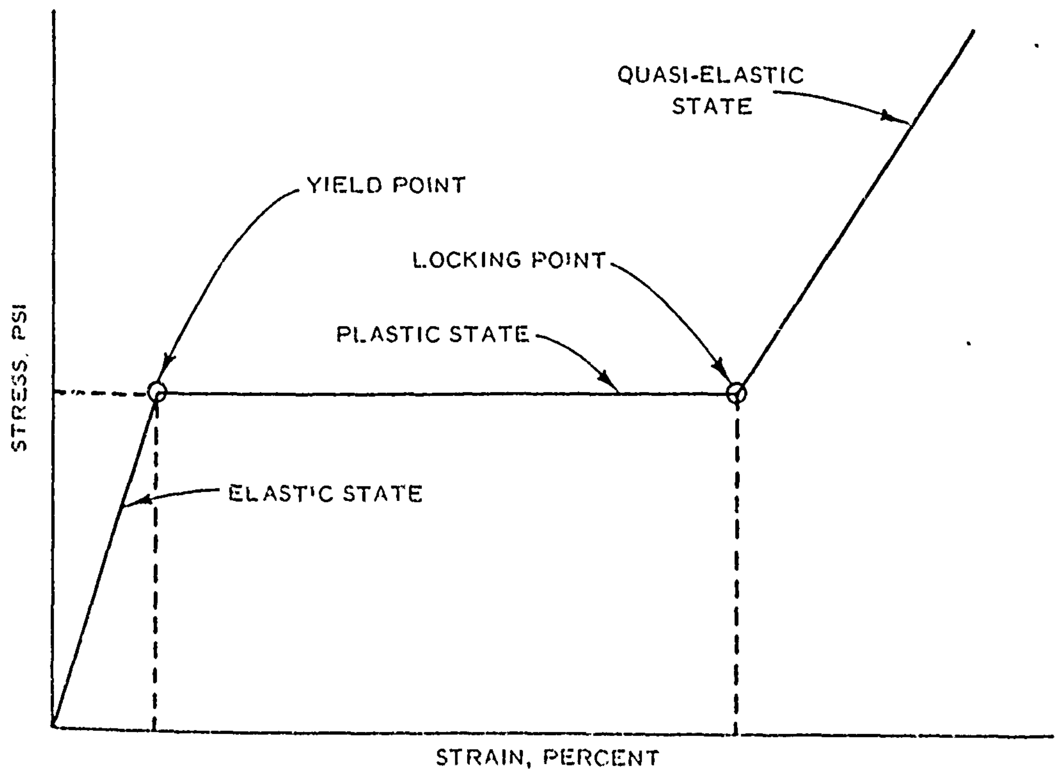


F[illegible]. Pressure-volume relation for an elastic-rigid locking solid

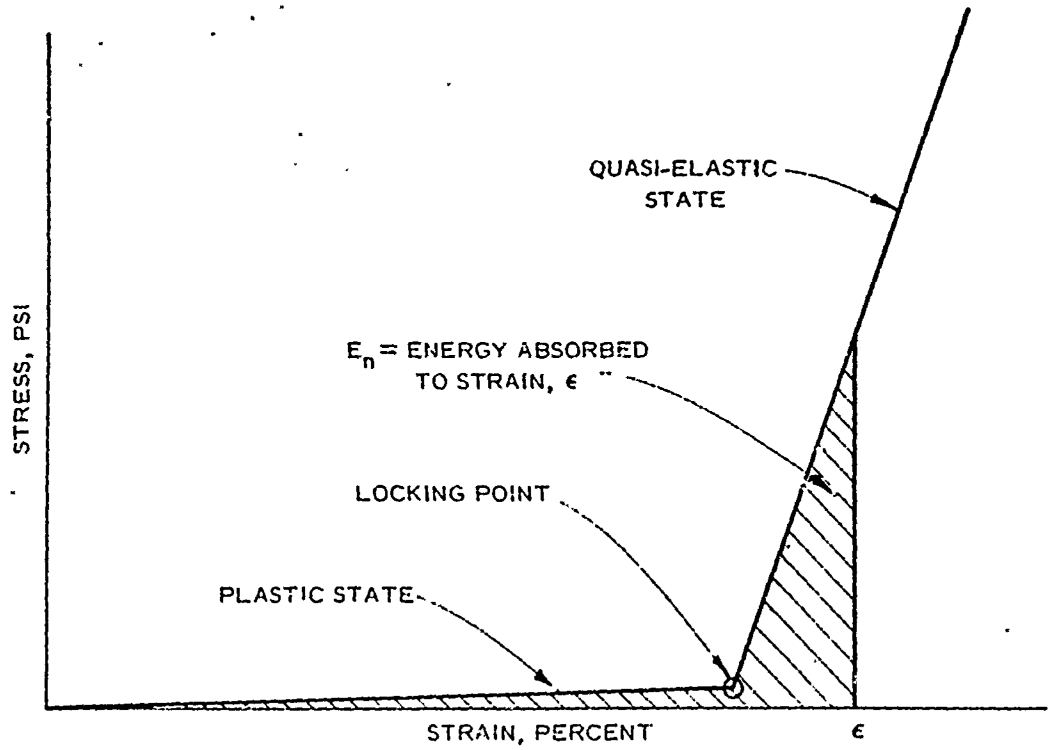


a. PLASTO-ELASTIC (SIMPLE-RIGID) MATERIAL

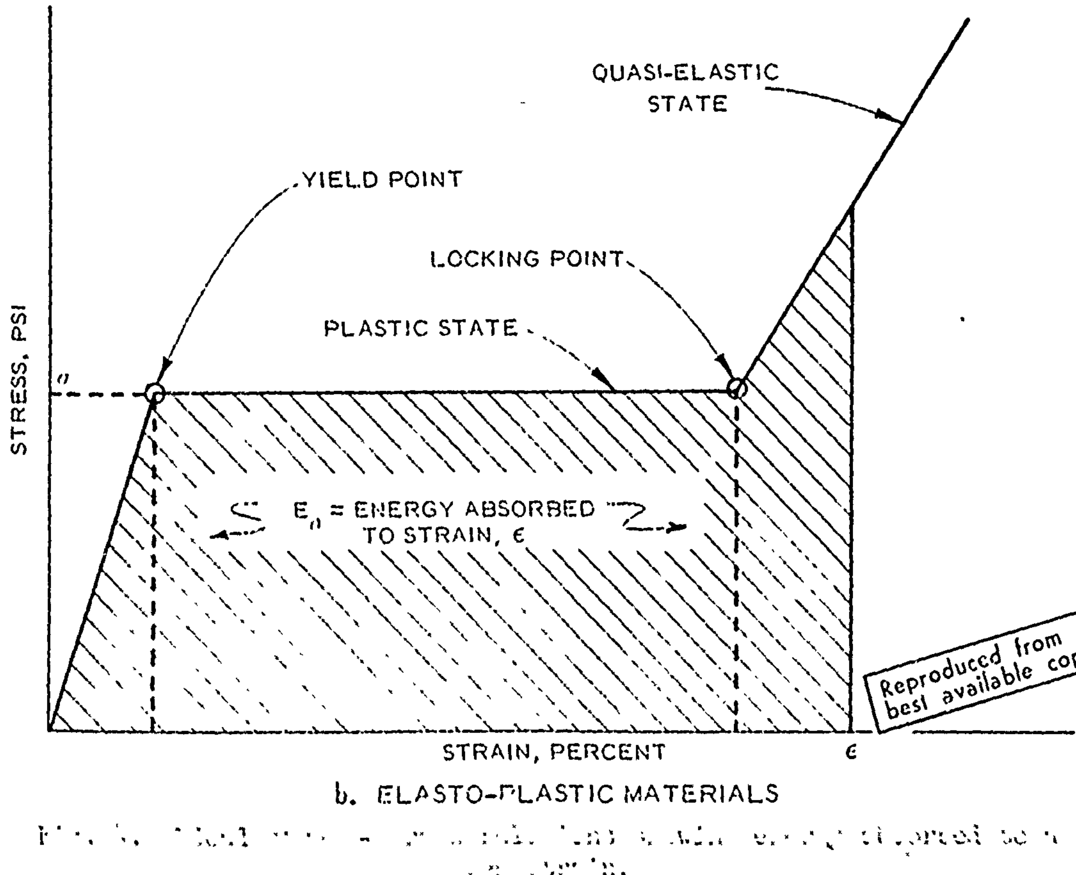


b ELASTO-PLASTIC (ELASTIC-RIGID) MATERIAL

[illegible]



a. PLASTO-ELASTIC MATERIALS



b. ELASTO-PLASTIC MATERIALS

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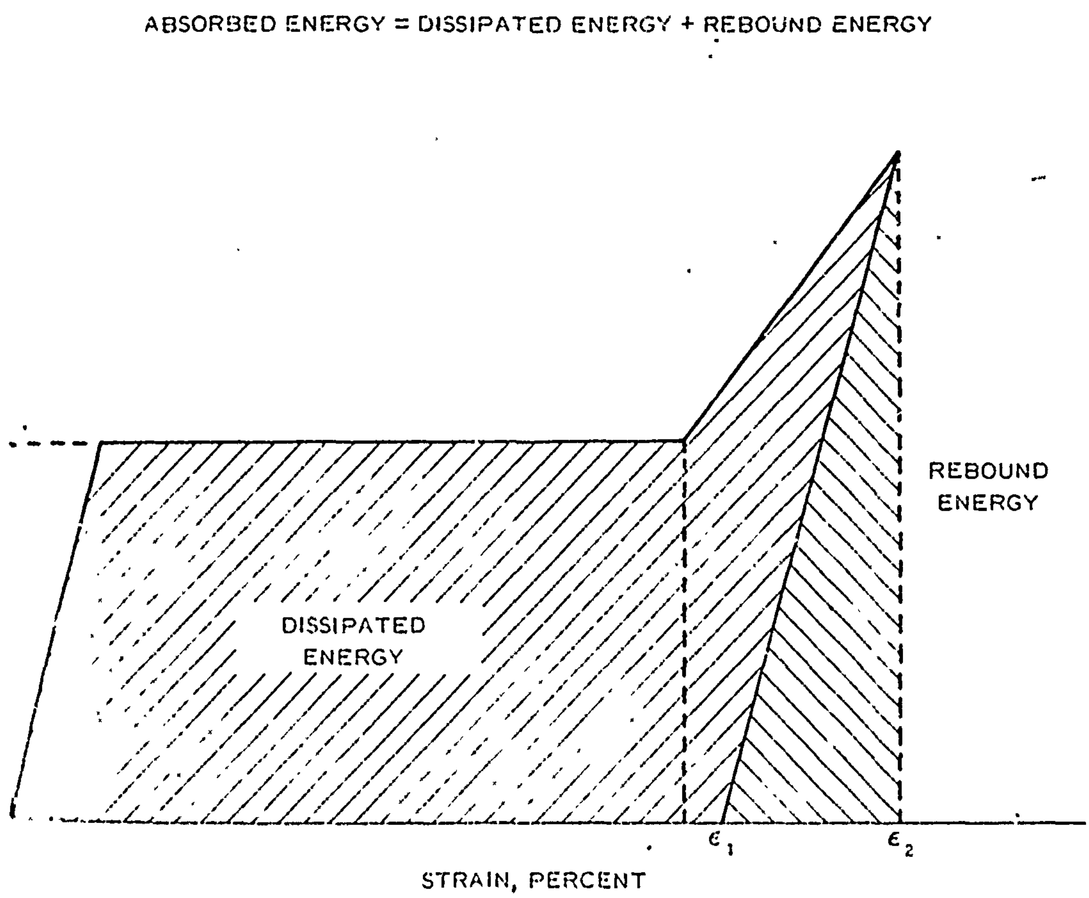
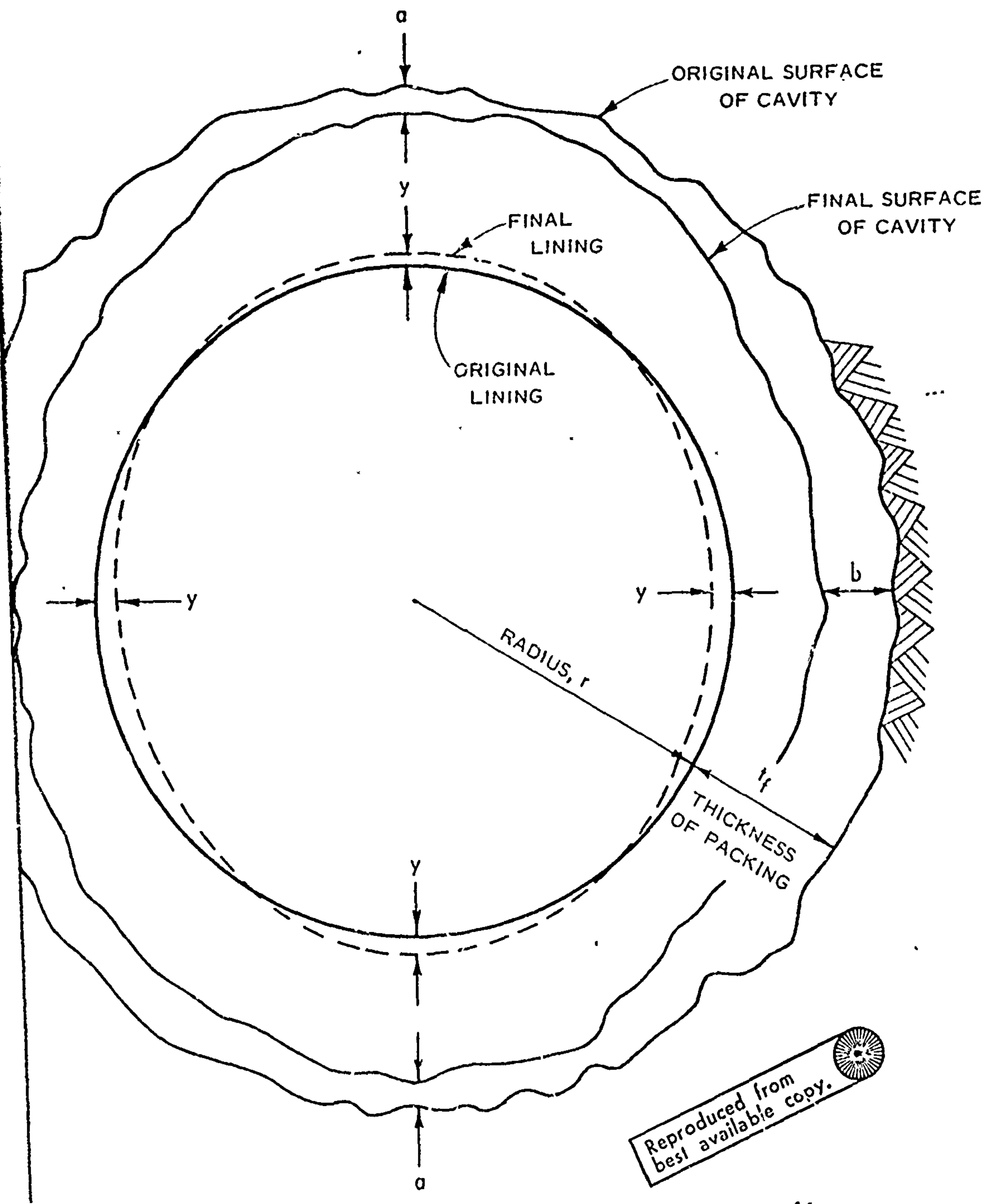
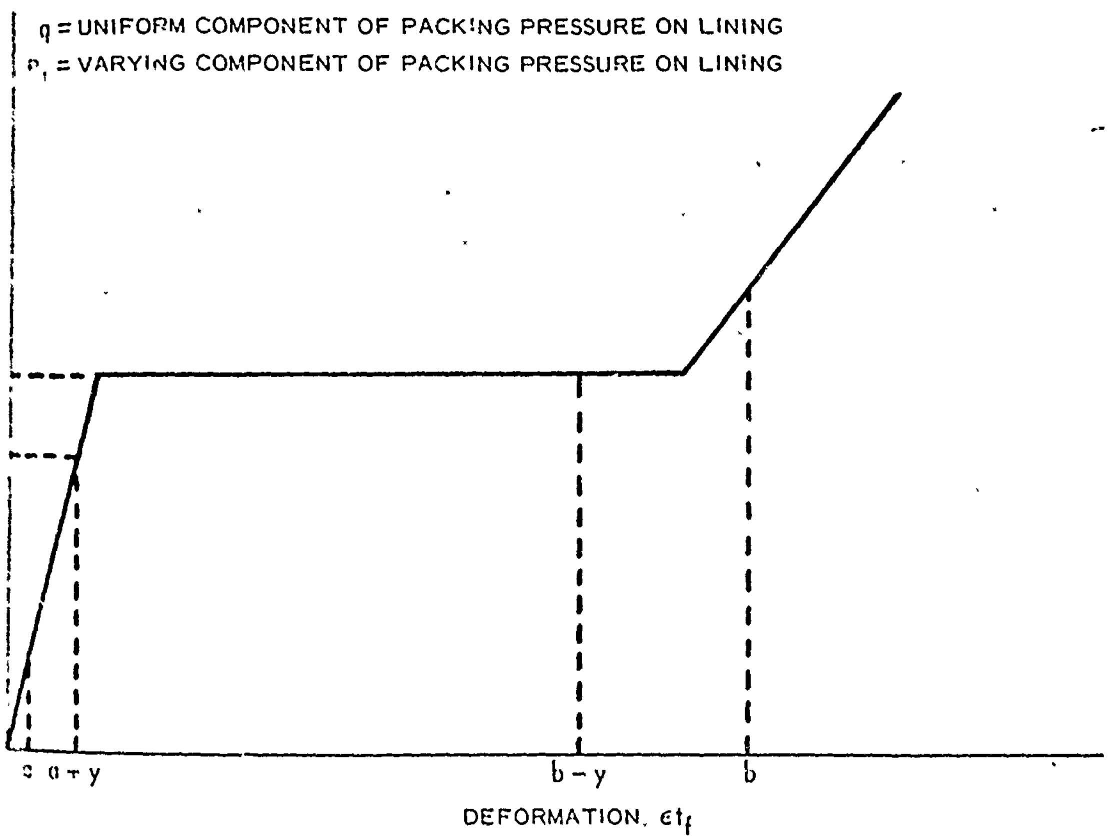


[illegible] stress-strain [illegible] showing absorbed energy, dissipated energy, and rebound energy (after [illegible] et al.)



[illegible] Deformation of lining and packing (after Newmark[illegible])



Ideal load-compression relation for packing (after Newmark[22])

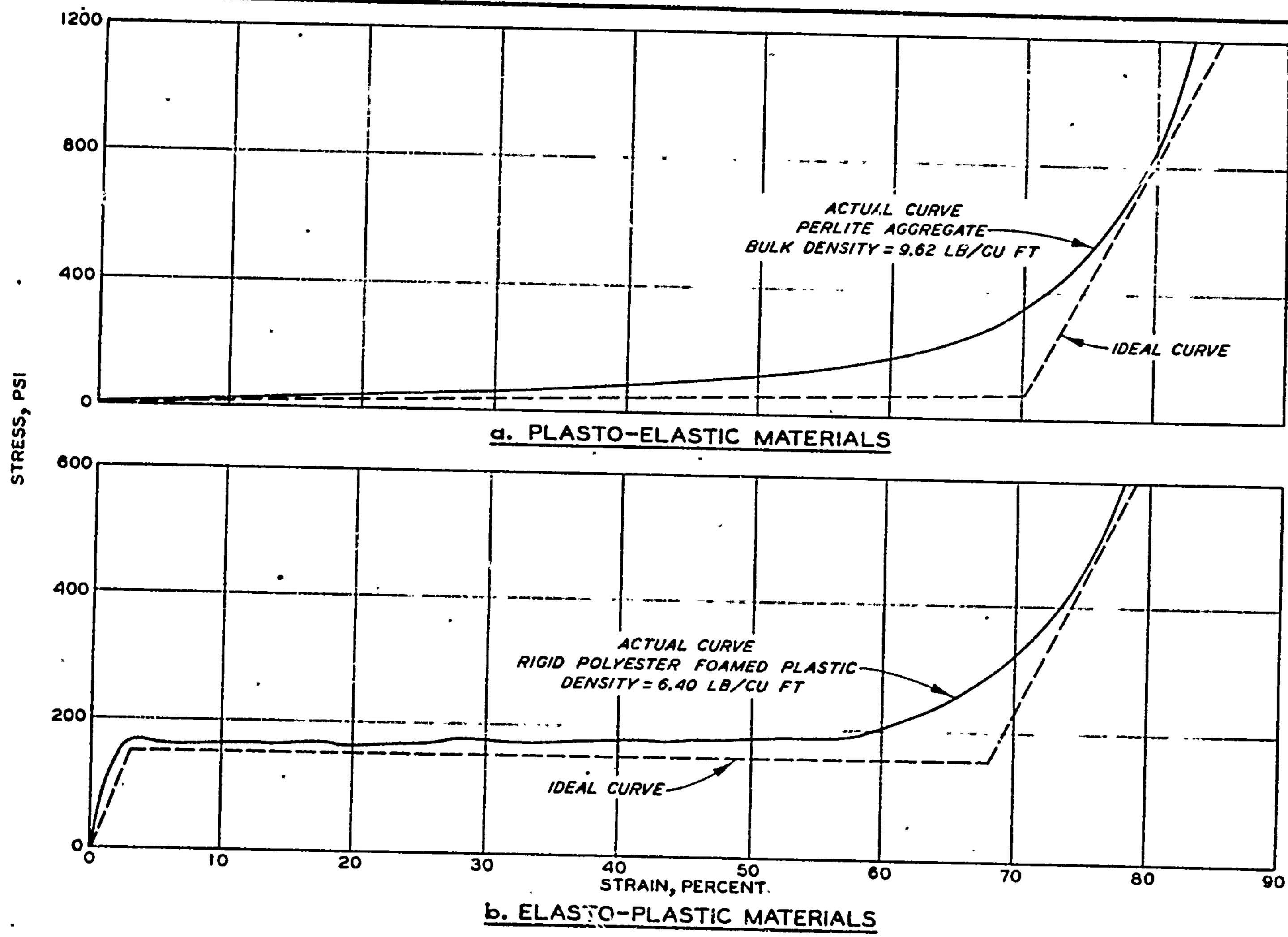
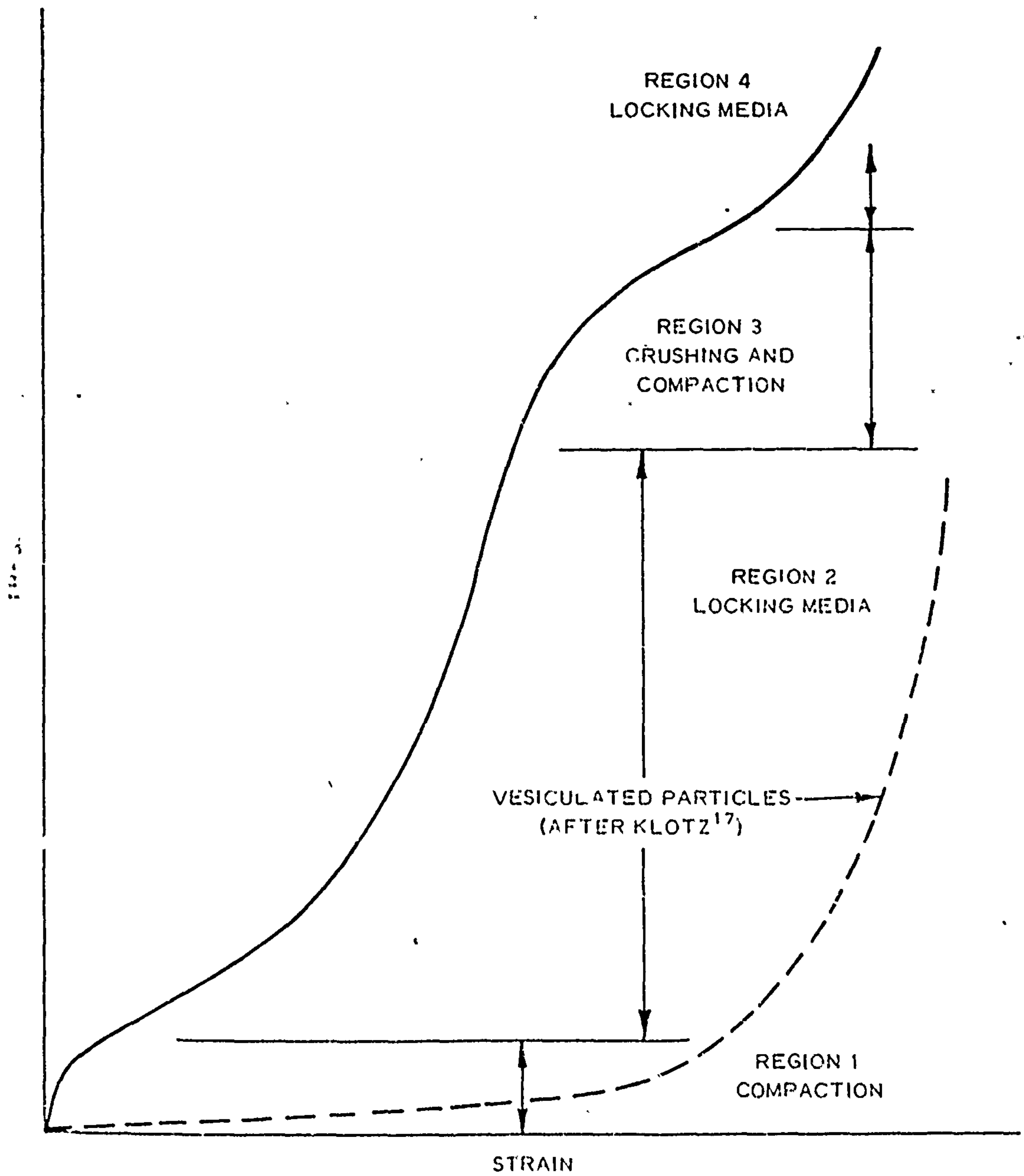


Fig. 8. IDEAL AND TYPICAL STRESS-STRAIN RELATIONS (AFTER KLOTZ[17])


REGION 4
LOCKING MEDIA
REGION 3
CRUSHING AND
COMPACTION
REGION 2
LOCKING MEDIA
VESICULATED PARTICLES
(AFTER KLOTZ[17])
REGION 1
COMPACTION
STRAIN

[illegible]

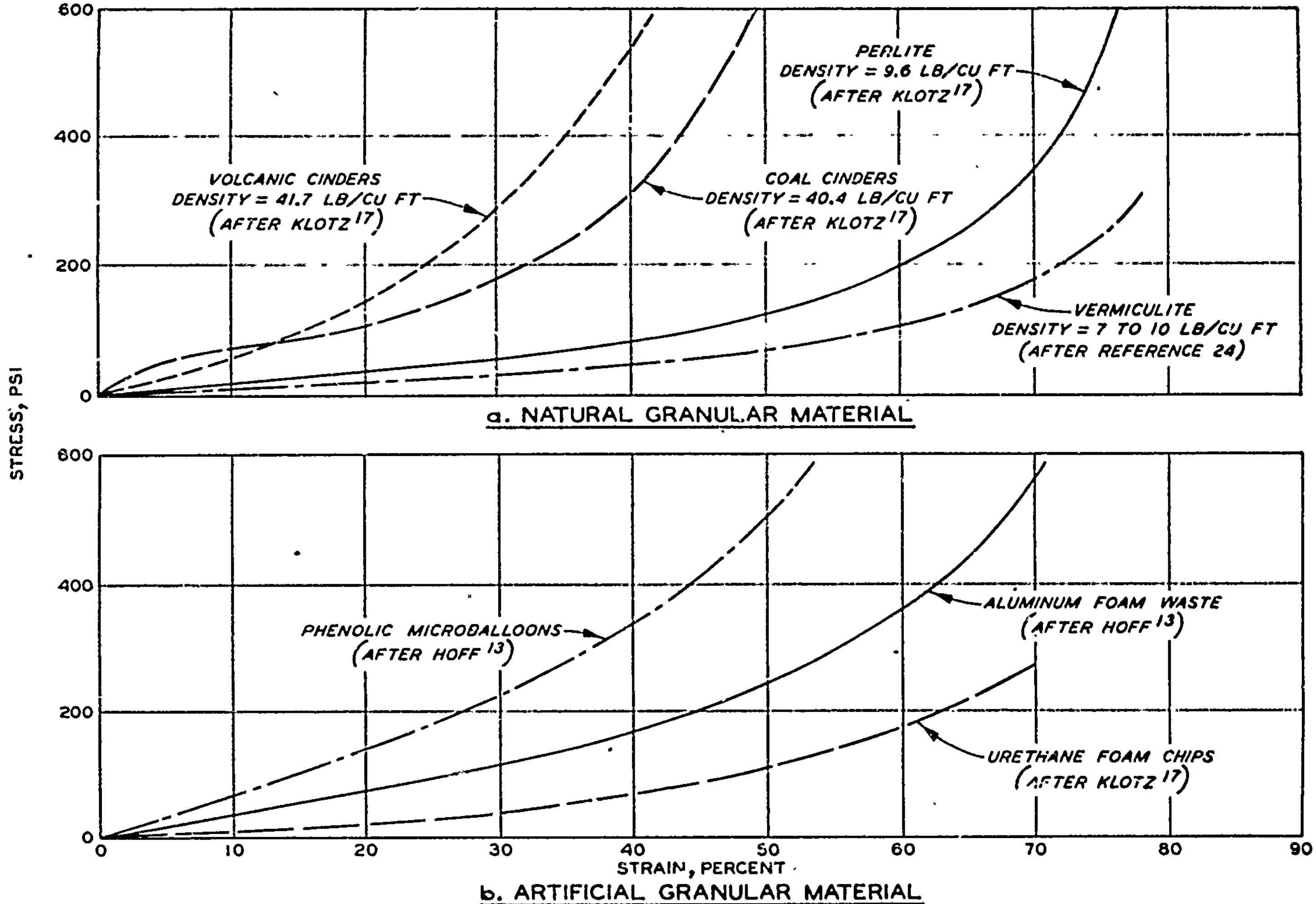


Fig. 10. TYPICAL STRESS-STRAIN CURVES FOR GRANULAR PLASTO-ELASTIC MATERIALS

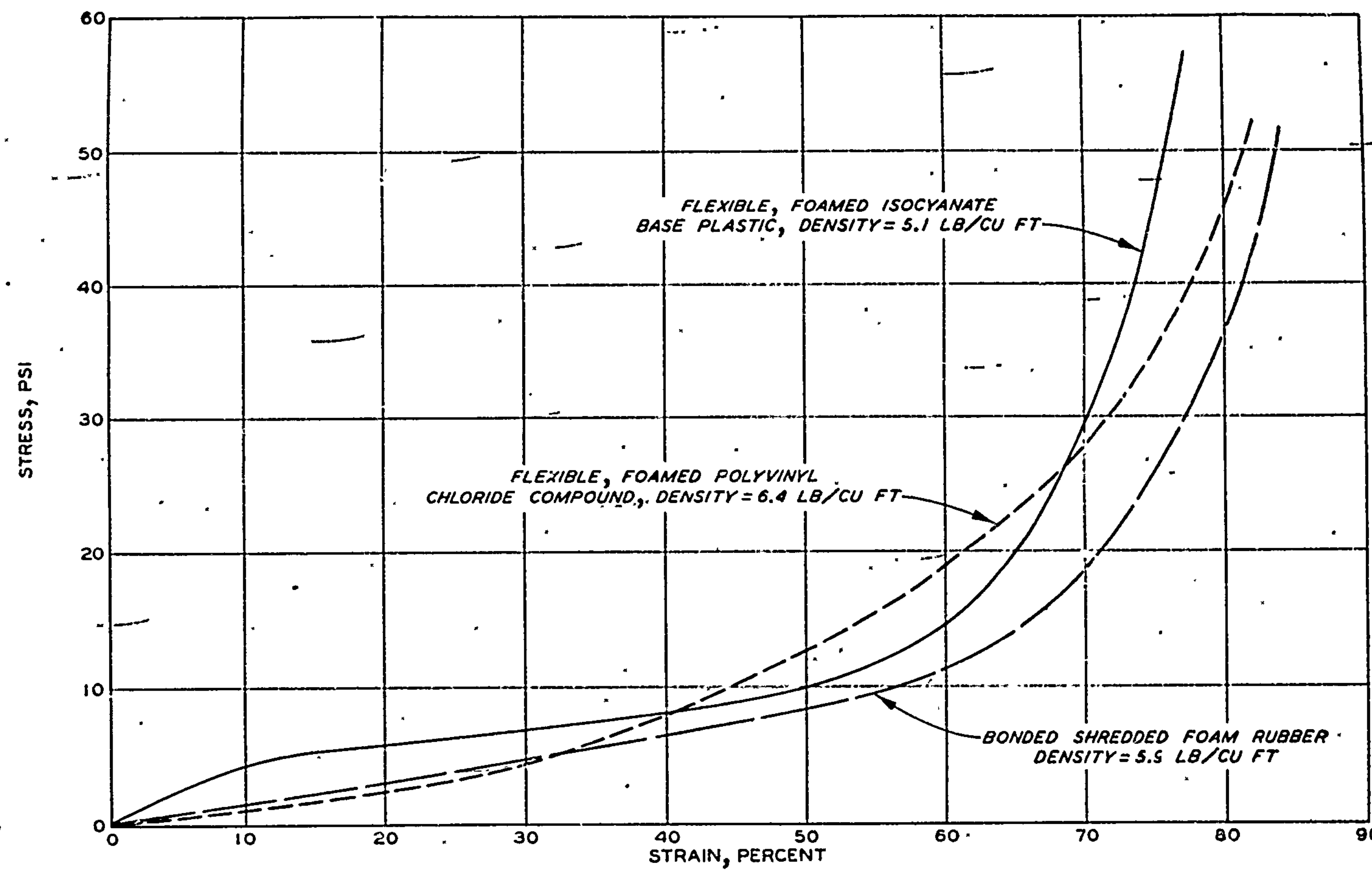


Fig. 11. TYPICAL STRESS-STRAIN CURVES FOR FOAMED PLASTO-ELASTIC MATERIALS (AFTER ALI[1])

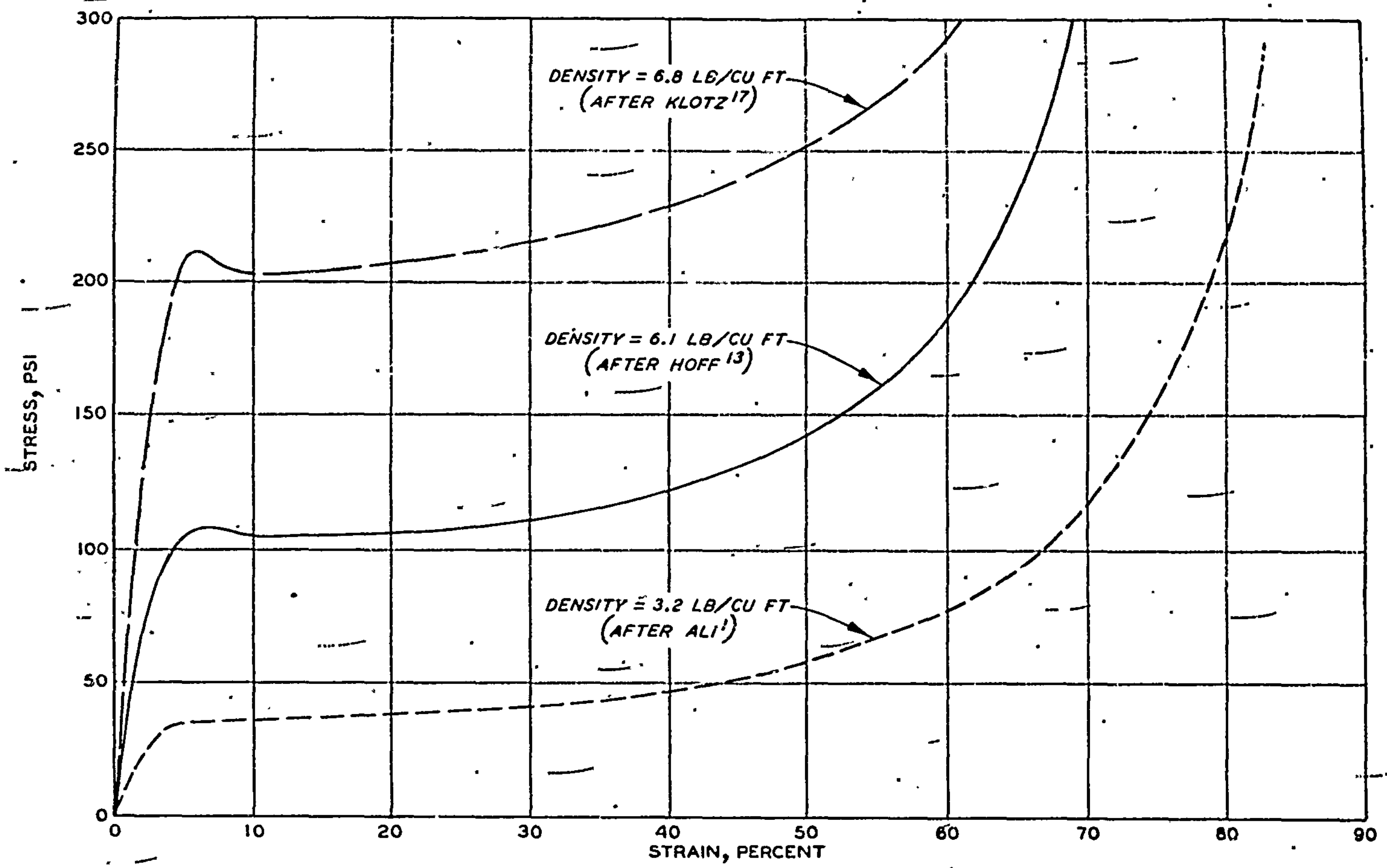


Fig. 12. TYPICAL STRESS-STRAIN CURVES FOR URETHANE AND POLYURETHANE RIGID FOAMED PLASTICS

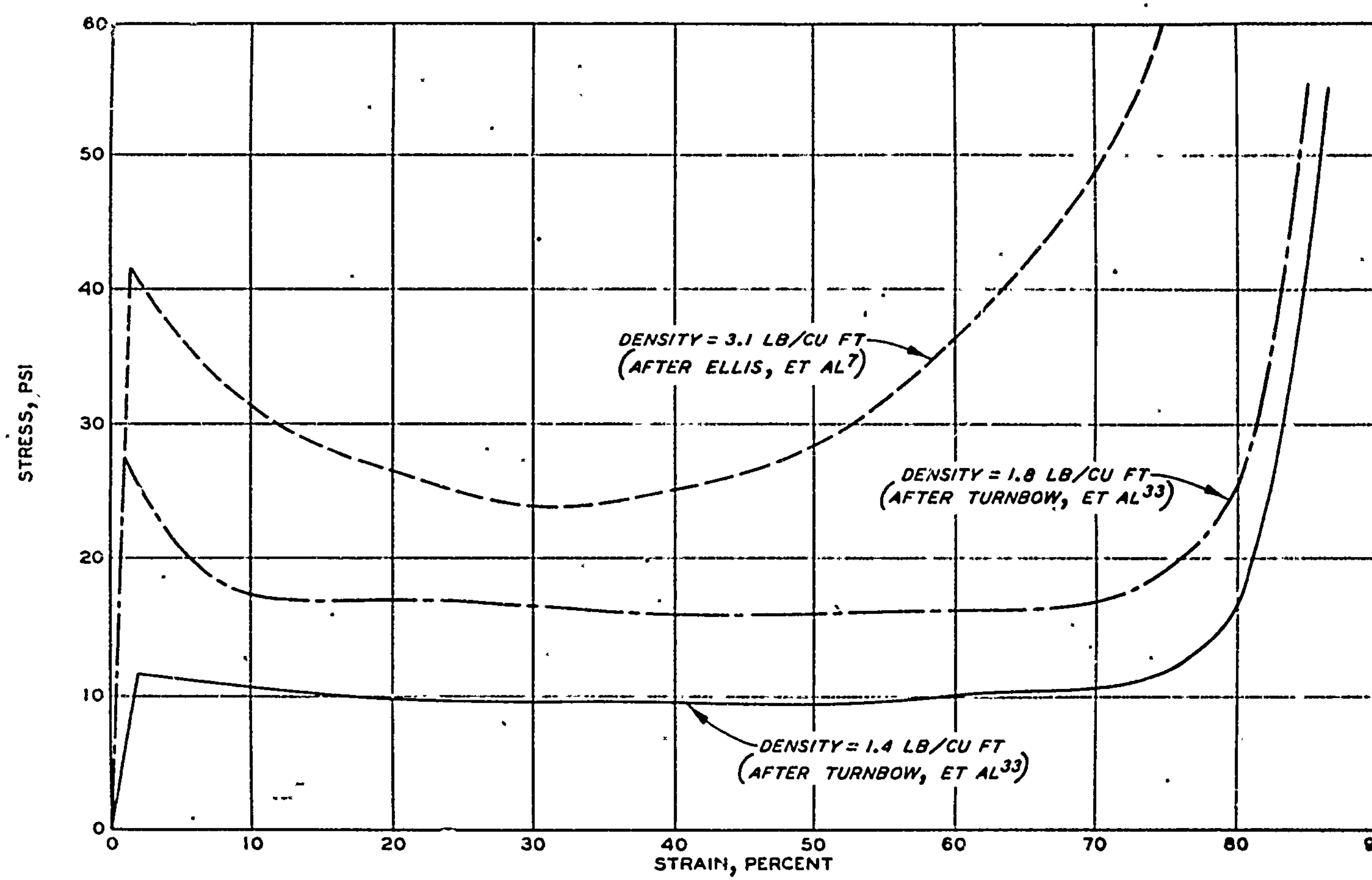


Fig. 13. TYPICAL STRESS–STRAIN CURVES FOR PAPER HONEYCOMBS

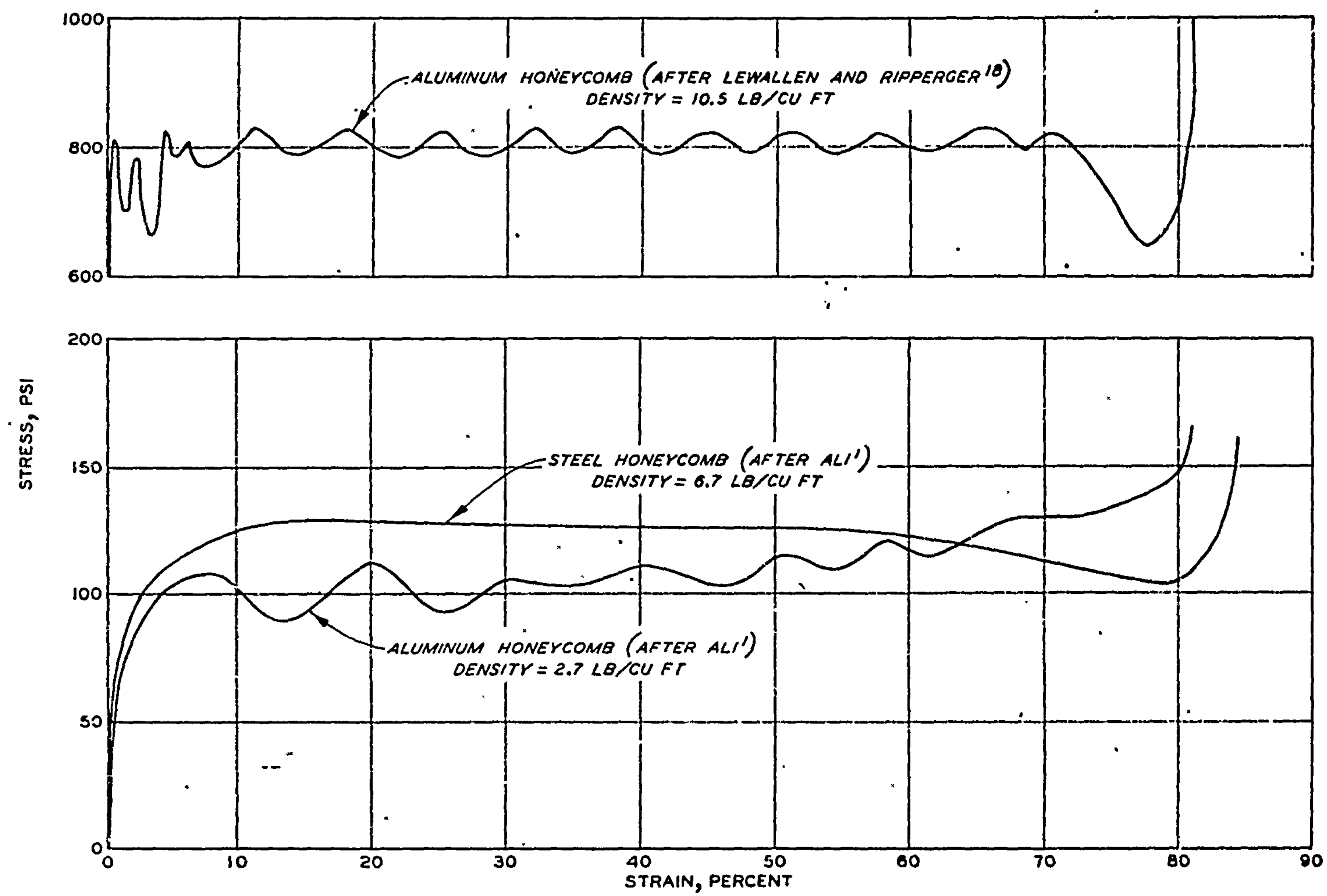


Fig. 14. TYPICAL STRESS-STRAIN CURVES FOR METALLIC HONEYCOMBS

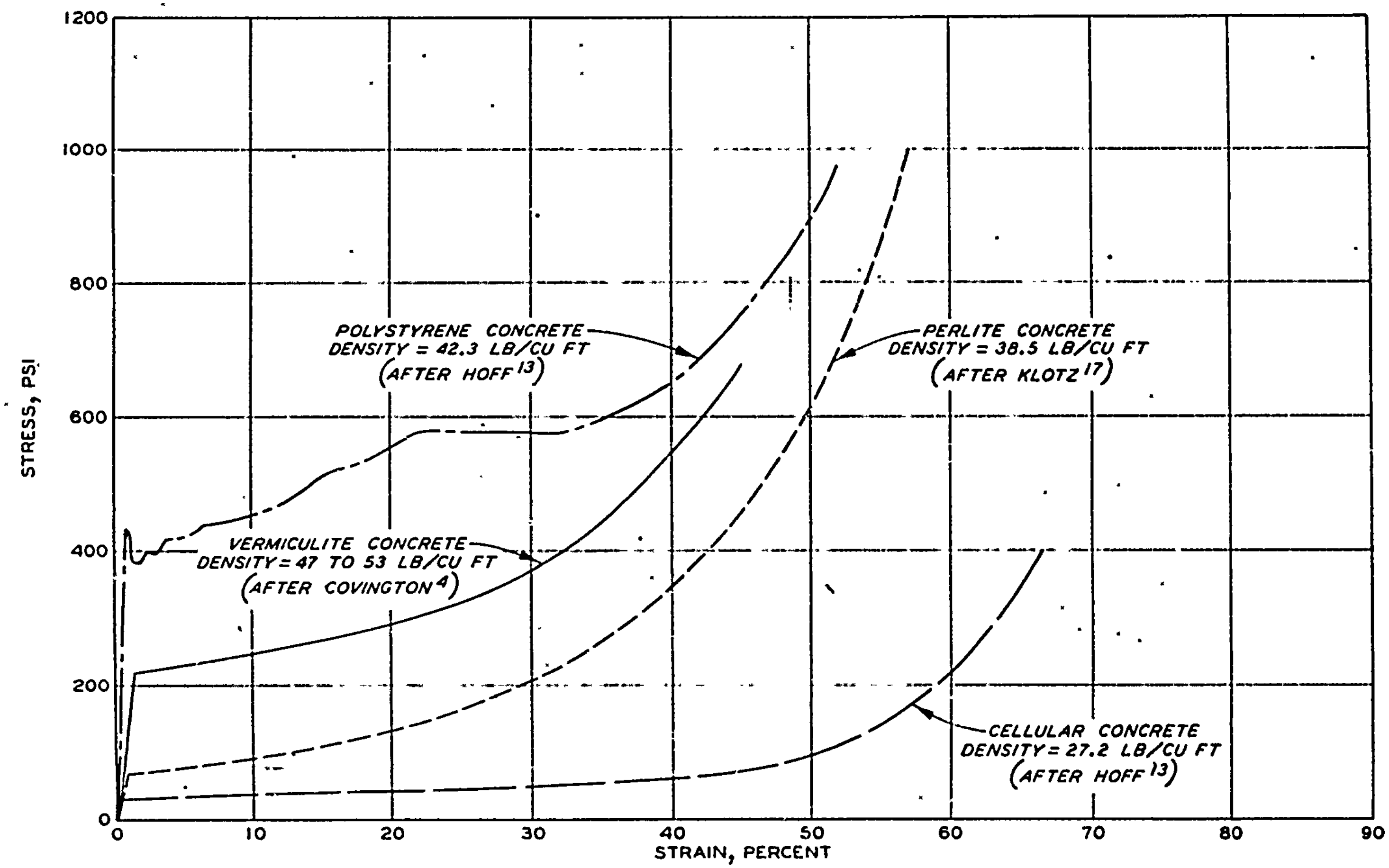


Fig. 15. TYPICAL STRESS-STRAIN CURVES FOR INSULATING CONCRETES

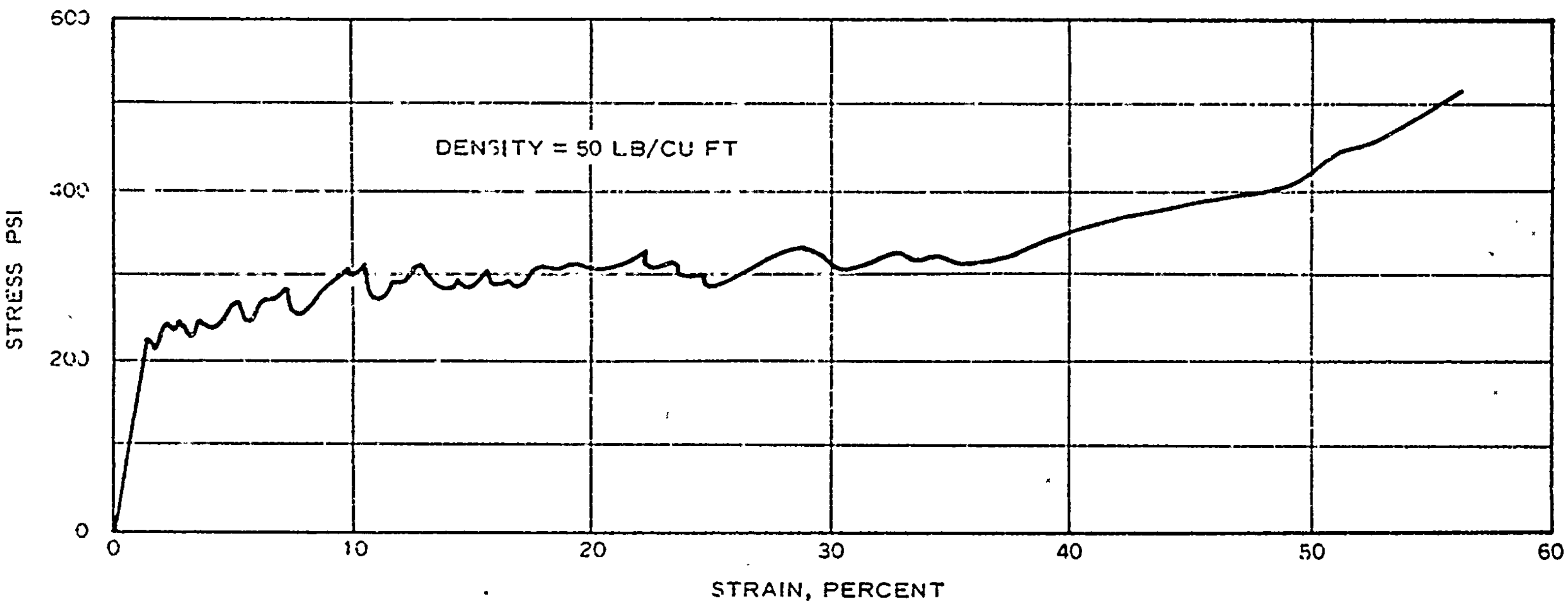


Fig. 16. Typical stress-strain curve for foamed sulfur (after Nevill[21])