MISCELLANEOUS PAPER NO. 6-928

SHOCK-MITIGATING MATERIALS

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G. C. Hoff

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U. S. Army Engineer Waterways Experiment Station
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FOREWORD

This paper was prepared at the request of Brigadier General W. C. Hall, USA, Ret., Editor, THE MILITARY ENGINEER, Washington, D. C., for consideration for publication therein. Publication of the paper was approved by the Office, Chief of Engineers on 6 September 1967. Approval for use of a Defense Atomic Support Agency (DASA) photograph was obtained from DASA, Test Command, Albuquerque, N. M., on 22 August 1967.

The work upon which the paper is based was conducted by the Concrete Division of the Waterways Experiment Station, Corps of Engineers, for DASA, Washington, D. C., and Albuquerque, N. M., under the supervision of Mr. Bryant Mather, Chief, Concrete Division, and Mr. James M. Polatty, Chief, Engineering Mechanics Branch, Concrete Division.

Colonel John R. Oswalt, Jr., CE, was Director of the Waterways Experiment Station during the preparation of this paper. Mr. J. B. Tiffany was Technical Director.

27 July 1967

SHOCK-MITIGATING MATERIALS

by

George C. Hoff*

In the design and construction of underground structures, there is a need for knowledge of the structure-medium interaction with advances in weapons development. The difficulty in understanding structure-medium interactions and designing of buried structures have become further complicated by the introduction of complex ground motions and very high applied loads. Conservative design of buried structures to resist these high loads results in solutions that are extremely costly. Nevertheless, catastrophic failure of the structure 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 the 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. The Concrete Division of the U. S. Army Engineer Waterways Experiment Station (WES) at Jackson, Mississippi, has been investigating one concept for aiding the designer of deeply buried protective structures. This concept is the use of shock-mitigating backpacking materials around the structure.

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Backpacking Design Considerations

In general, a suitable shock-absorbing backpacking should be a crushable material possessing a low crushing stress level and a high degree of compressibility. By possessing these characteristics, the material should dissipate and possibly reflect 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 overpressures, the scope of interest of backpacking materials is usually limited to design overpressures less than 1000 psi; that is, the assumption is made that the magnitude of the stress transmitted to the structure through the backpacking will be less than 1000 psi. Assuming single-burst loading where tendency is for the cavity to close, deformations of the backfill to accommodate this tendency should be approximately 50 percent. In other cases it may be considerably less.

The majority of the materials investigated both in the past and at present generally fall into two distinct categories: (a) materials having no distinct yield point and some degree of compressibility, and (b) materials possessing a distinct yield point and some degree of compressibility. Ideally, these materials can be represented by stress-deformation curves for plasto-elastic materials (fig. 1a) and elasto-plastic materials (fig. 1b), respectively. The amount of energy absorbed per unit volume by the backpacking can be determined as the product of the deformation and the unit force in the material, or simply, by the area under the stress-deformation curve. It then becomes obvious from the shape of the curves in fig. 1 that elasto-plastic materials are more efficient energy absorbers than plasto-elastic materials. Both materials are under consideration for use as backpacking; however, because the plasto-elastic materials may be more economical, they may be more attractive when large volumes are necessary. 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.

When the closure of the cavity containing a backpacked liner is uniform, the deformation of the backpacking will also be uniform, hence, if the backpacking is homogeneous and isotropic, the circumferential stress transferred to the structure will also be uniform. The magnitude of the stress 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. 2, 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 buckling, and must be able to deform sufficiently, without failure or fracture, in order to develop the required resistance.

Notations a and b in fig. 2 represent the displacements 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. 3), 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. If 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 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. 3, the larger the net differential pressure, 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 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 plasto-elastic materials but with a little more difficulty as it is relatively impossible for a lining interacting with the progressively increasing stress-strain relation of a plasto-elastic material to develop a resistance characterized by a nearly uniform compression on all sides.

Materials

The two ideal stress-strain relations shown in fig. 1 define the properties of a variety of materials. Fig. 4 shows the relation between the ideal and the typical stress-strain curves for both types of material.

The typical curve shown in fig. 4a represents the stress-strain relation for materials that do not possess a definite yield point (plasto-elastic) but are still very compressible, either elastically or inelastically. Granular materials, either naturally occurring such as volcanic cinders, or artificially produced such as expanded clay, shale, vermiculite, and perlite, or foamed plastic and metals in a granular form are representative for this type of curve. Some plastics and rubbers also possess these characteristics.

Fig. 4b represents the typical stress-strain curve for elasto-plastic materials compared with the ideal curve. Insulating concretes, rigid-foamed plastics, honeycombs, and other foamed materials such as gypsum, glass, epoxy, and sulphur are good representatives of this class of material, although some granular and other materials may also exhibit this type of behavior.

The ultimate selection of a backpacking material for a given use should depend upon the actual service conditions and the final cost of the in-place material. Since a variety of materials appear to possess the desirable characteristics of a suitable backpacking, ideally, the designer should thoroughly examine all of the available materials before making his selections. To aid the designer in his selection, materials that lend themselves to easy handling and placing, using conventional construction equipment are being investigated at WES. One such material that appears to be very promising is cellular concrete.

Cellular concrete, which is also called "foamed" concrete, is usually made for cast-in-place operations by adding predetermined amounts of an organic-based foam to a portland-cement slurry either with or without additions of a sand or filler material. The foam, which resembles the shaving cream obtained from aerosol cans, contains numerous little individual bubbles, which when coated with a cement paste provide the cellular nature of the hardened material. In most cases the foam can be mechanically blended into the slurry using conventional concrete and plaster mixers. In some instances, ready-mix trucks can also be used to do the blending. The cellular concrete in the unhardened condition is easily pumped with positive-displacement-type pumps for horizontal distances of 600 ft and against heads of 50 ft without appreciably changing the density of the concrete.

For backpacking purposes, a neat cellular concrete can be made at unhardened densities of 20 to 50 lb/cu ft with water-cement ratios (by weight) from approximately 0.6 to 1.1 depending on the compressive strength desired. Fig. 5 shows a typical yield-stress unhardened-density relation for a neat cellular concrete having a water-cement ratio of 0.76.

The equipment shown in fig. 6 is typical of that which can be used for the fabrication and pumping of cellular concrete. The design of this equipment was recommended by WES. Since its construction, it has been successfully used under the direction of WES to place approximately

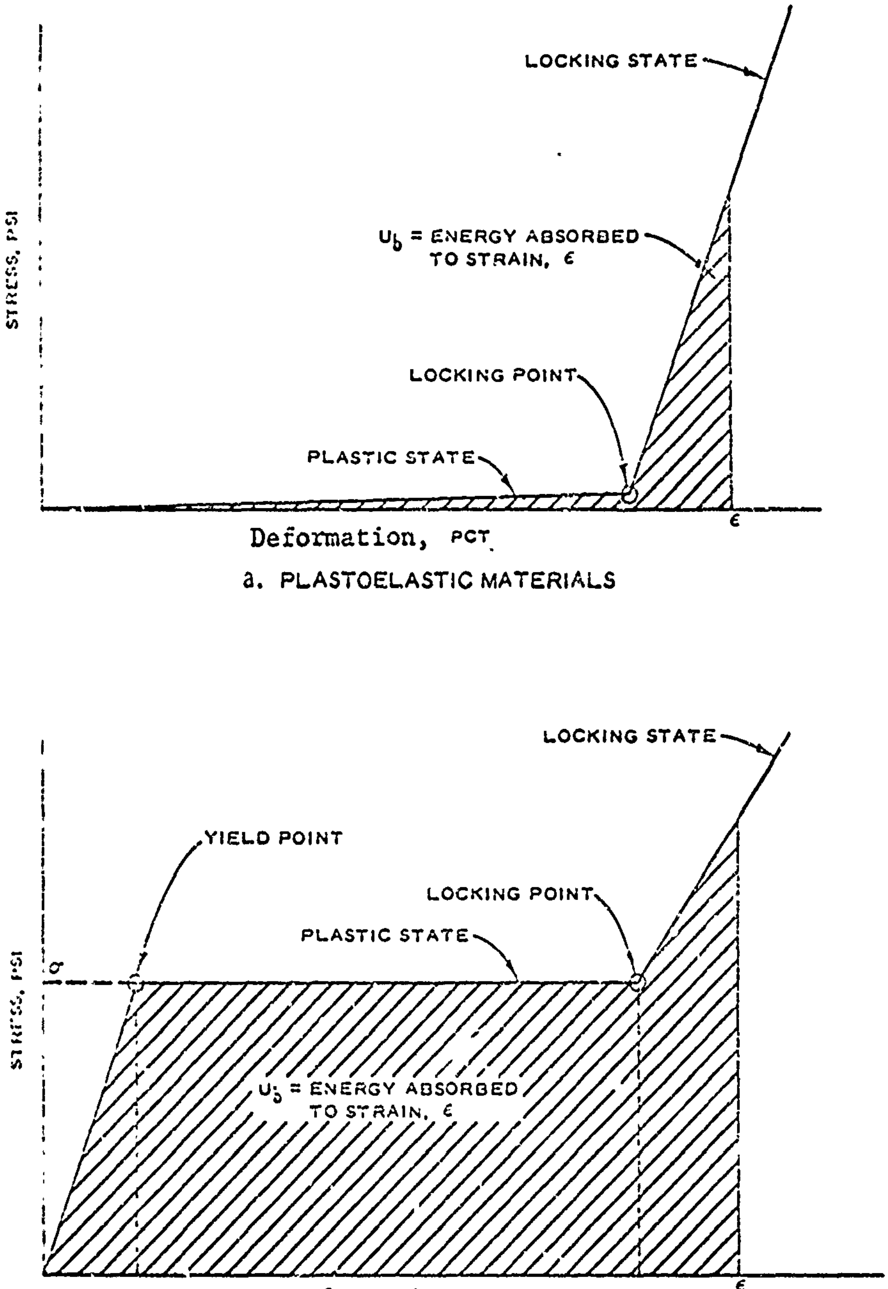
19,000 cu yd of neat cellular concrete as backpacking for deeply buried protective structures. The unit consists of two 1/2-cu-yd plaster mixers that do the blending of the foam and slurry; two automatic foam generation systems, one for each mixer, with reset timers that put an identical amount of foam into each batch if desired; two auxiliary water meters, one for each mixer, for use in modifying the water content of the slurry if necessary; a large concrete hopper; and a large open-throat positive displacement pump for moving the concrete into the formwork. The cement slurry is introduced into the mixers by means of an auxiliary metering system that puts exact amounts of a premixed slurry in each mixer. It can also be made at the mixer using dry cement and water from the auxiliary water meters. The second method is more time consuming. When the slurry is premixed, the equipment, when operated properly, has a capacity of 30 cu yd an hour.

The formwork necessary to contain the cellular concrete needs to be watertight as the cellular concrete will leak out of very small holes or cracks. Once in the form, the cellular concrete requires no rodding or vibrating, and because of its very fluid consistency, seeks its own level. Fig. 7 shows a typical horizontal concrete barrel that has been backpacked with cellular concrete.

The 19,000 cu yd of cellular concrete placed using the equipment shown in fig. 6 was done at an in-place cost of approximately $12.50 per cu yd, including materials and labor. For comparison purposes, similar barrel configurations were backpacked with 600 cu yd foamed polyurethane plastic at a cost of approximately 25 times that of the cellular concrete.

The cellular concrete does, however, have some limitations. Because of its very high porosity at the lower densities, it is susceptible to the infiltration of groundwater. This would reduce its effectiveness in shock mitigation. If water is a problem, conventional construction techniques can be used, however, to exclude it from the area. The concrete also continues to increase in strength with time which would change the expected loading on the structure with time. By proportioning the concrete for strength at 90 days age, however, the effect of this increase would be minimized as the strength increases after 90 days are very small.

Additional work is currently being conducted at WES to develop new backpacking materials and to improve the quality of equipment and procedures for handling and placing existing materials that appear to have promise for use as backpacking.



a. PLASTOELASTIC MATERIALS

b. ELASTOPLASTIC MATERIALS

Figure 1. Ideal stress-strain relations showing energy absorbed to a given strain, ε .

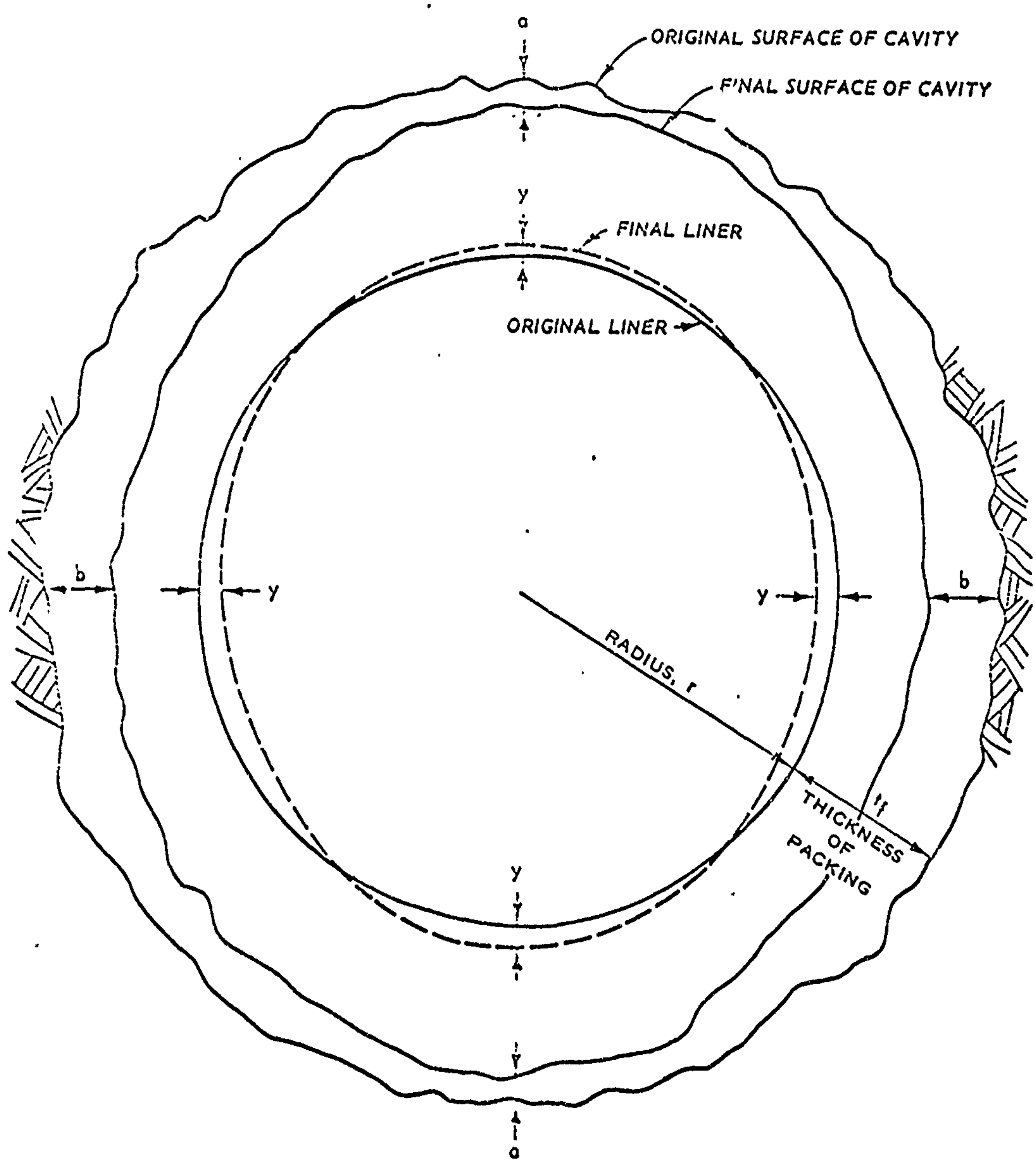


Figure 2. Deformation of liner and backpacking.

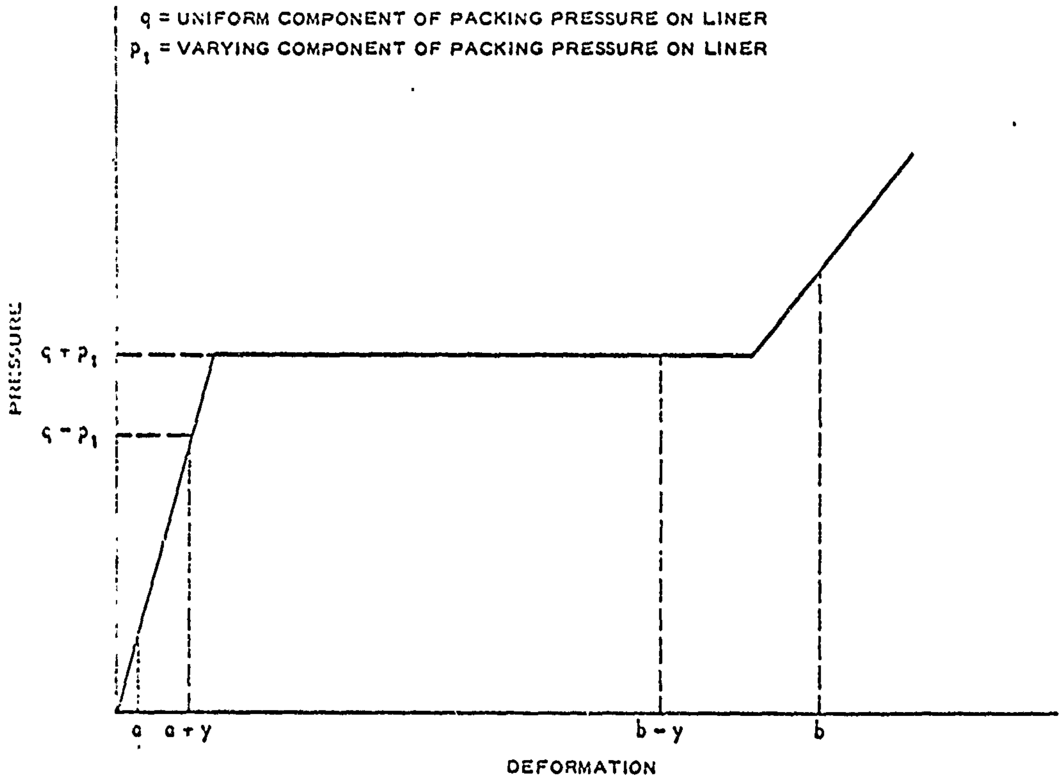


Figure 3. Ideal elastoplastic load-compression relation for backpacking.

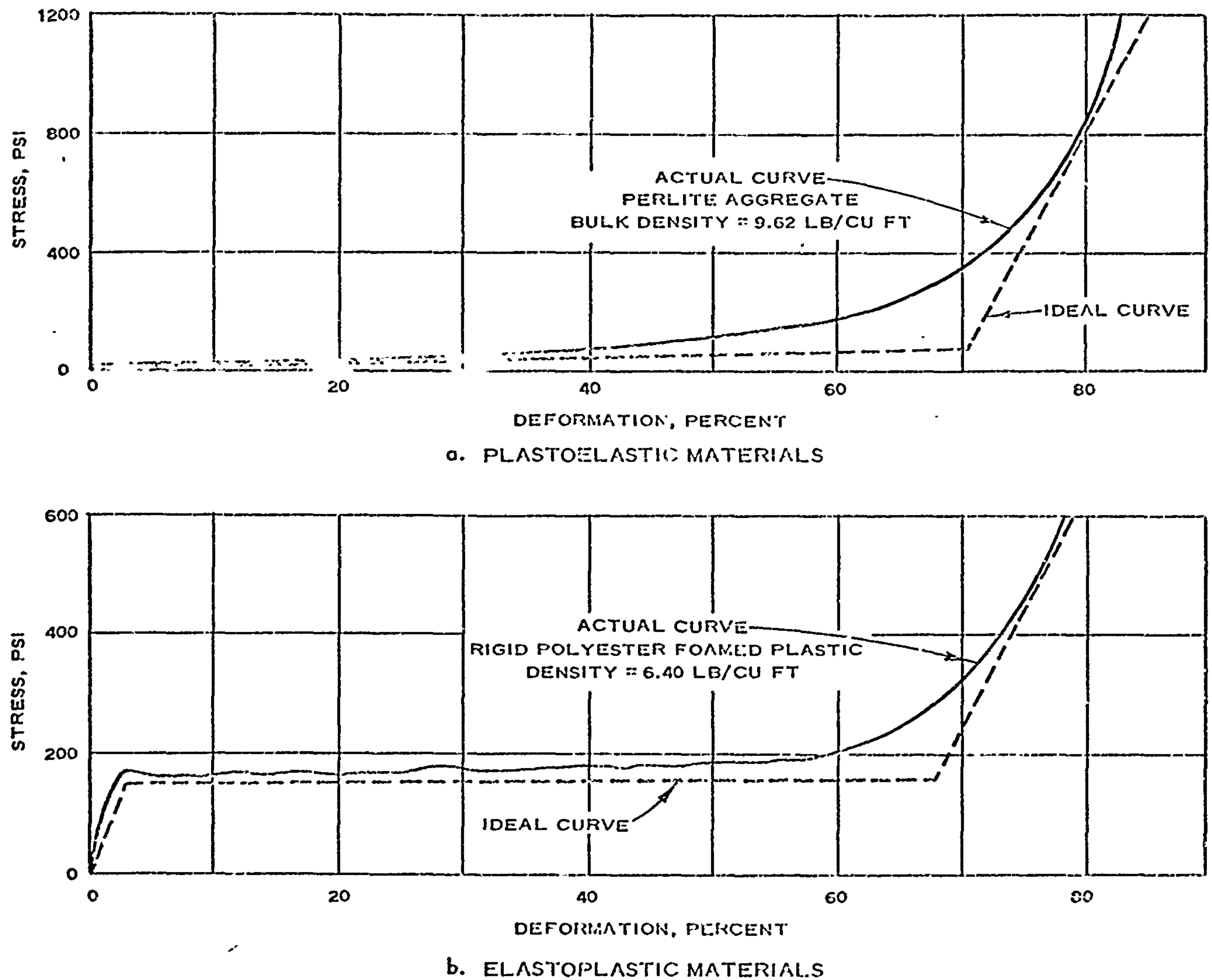


Fig. 4. Ideal and typical stress-strain relations

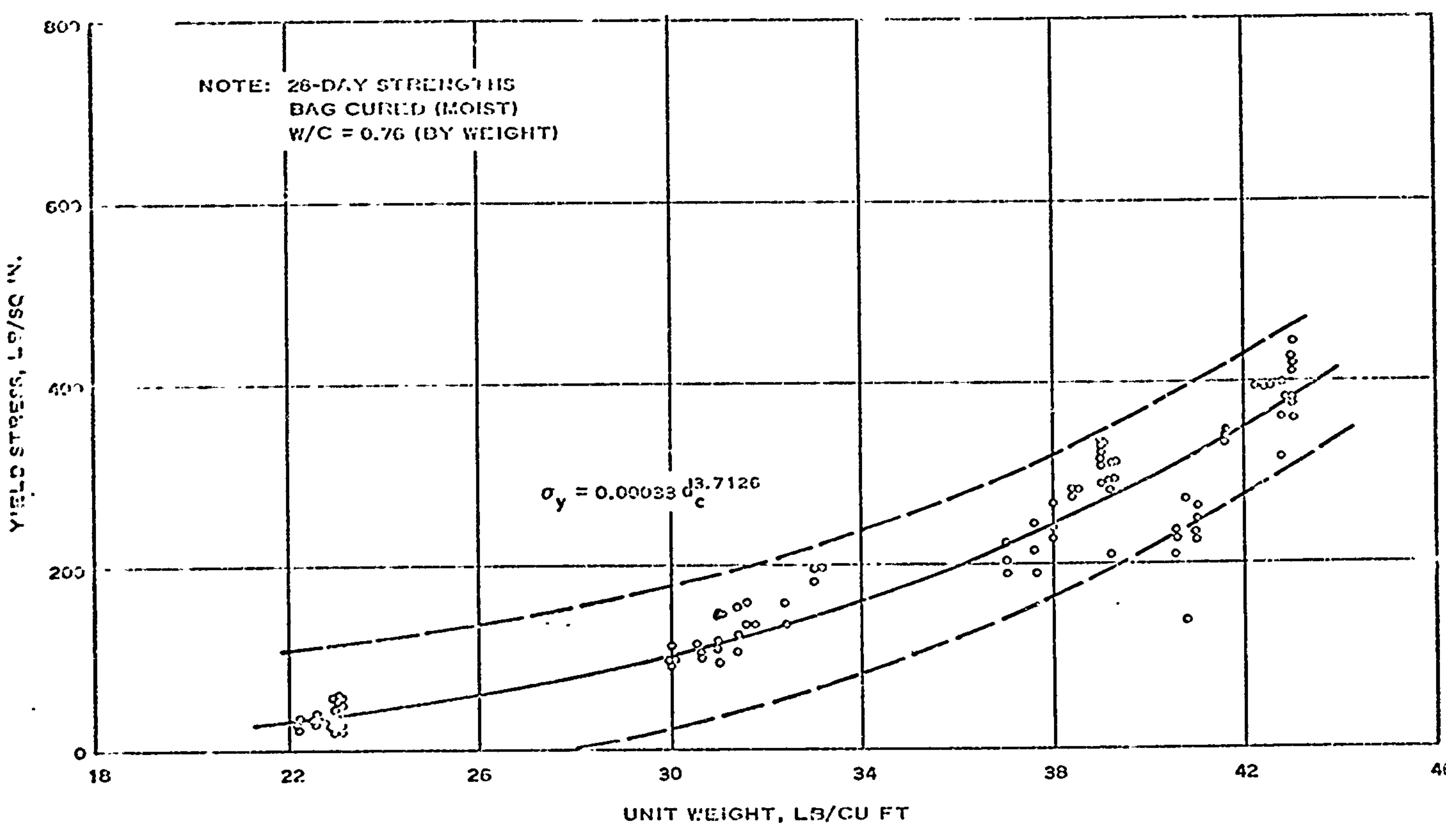
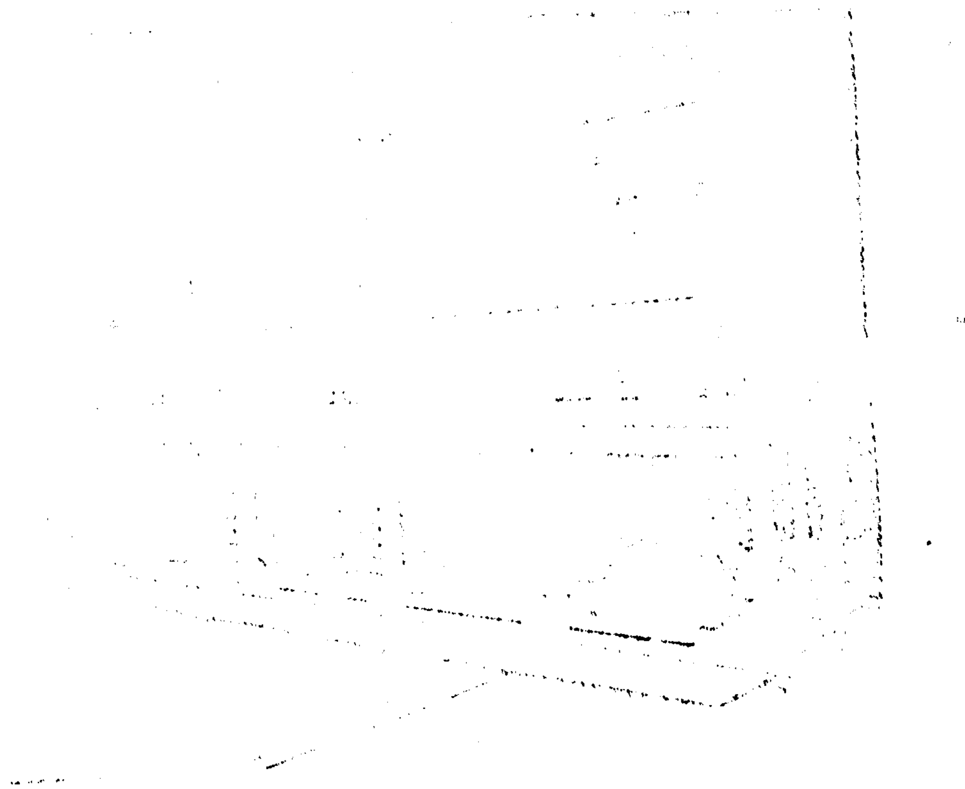
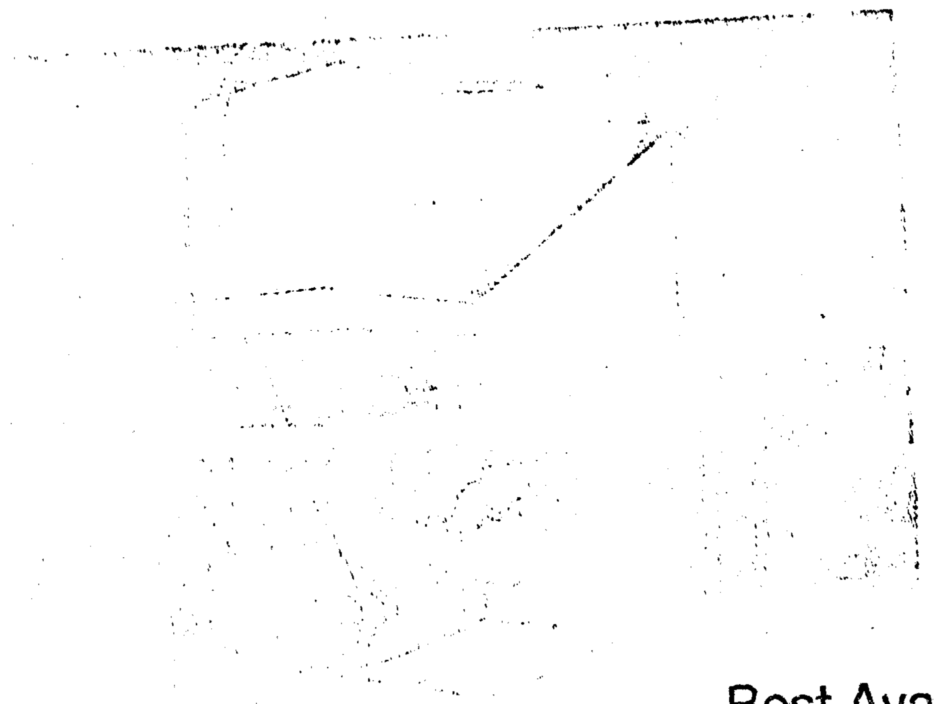


Fig. 5. Yield stress versus unit weight relation for cellular concrete with a water-cement ratio of 0.76



a. Front view.



b. [illegible] View.

Figure 6. Cellular Concrete Fabrication Equipment

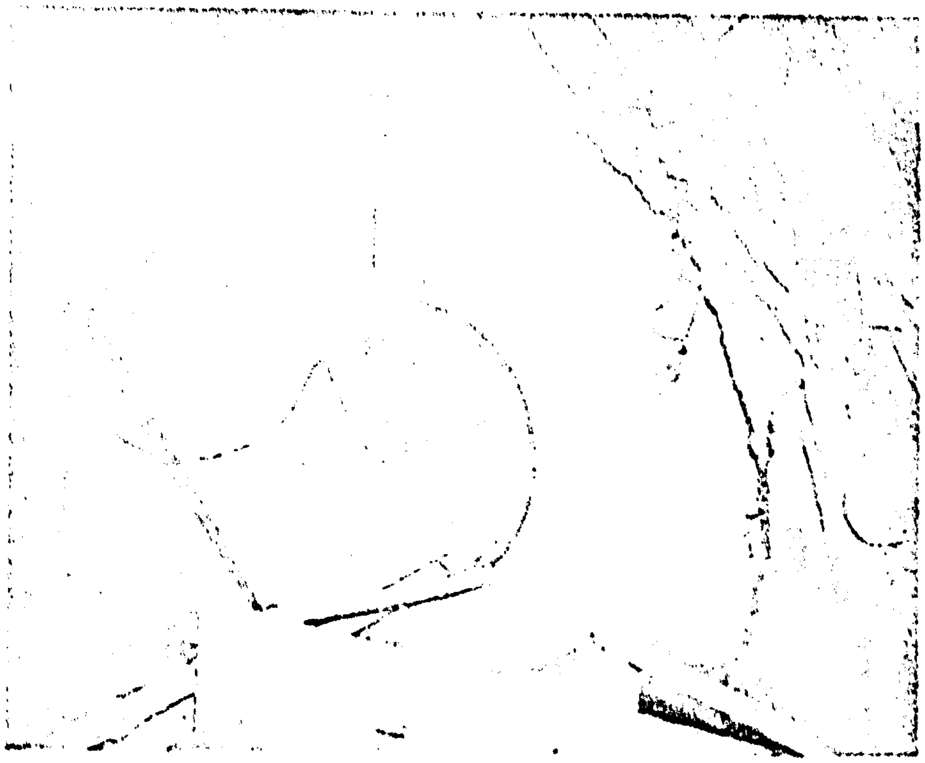


Figure 7. Typical Horizontal Barrel Backpacked with Cellular Concrete.