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Technical Report 227

# INVESTIGATION OF LIGHTWEIGHT SULFUR FOAM FOR USE IN FIELD APPLICATIONS

**John M. Dale**
**and**
**Allen C. Ludwig**

October 1969

SOUTHWEST RESEARCH INSTITUTE
CONTRACT DAAG-23-68-C-0001

CORPS OF ENGINEERS, U.S. ARMY
**COLD REGIONS RESEARCH AND ENGINEERING LABORATORY**
HANOVER, NEW HAMPSHIRE

22

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# PREFACE

The study reported herein was conducted by Southwest Research Institute (SwRI), San Antonio, Texas, under Contract No. DAAG-23-68-C-0001 with the U.S. Army Cold Regions Research and Engineering Laboratory. Mr. J.M. Dale was the SwRI Project Manager, and Messrs. A.C. Ludwig and W.B. Pratt contributed to the study. Mr. F.L. Russell was the USA CRREL Project Officer.

Inclusive dates of research were 9 August 1967 through 9 November 1968.

The study was a project of the Construction Engineering Branch (Mr. E.F. Lobacz, Chief) of the Experimental Engineering Division (Mr. K.A. Linell, Chief), USA CRREL.

Lieutenant Colonel John E. Wagner was the Commanding Officer/Director of the U.S. Army Cold Regions Research and Engineering Laboratory during the publication of this report and Mr. W.K. Boyd was Chief Engineer.

Citation of trade names is for information only and does not constitute official endorsement or approval.

## CONTENTS

## ILLUSTRATIONS

## TABLES

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# INVESTIGATION OF LIGHTWEIGHT SULFUR FOAM FOR USE IN FIELD APPLICATIONS

by

John M. Dale and Allen C. Ludwig

## INTRODUCTION

This study is a follow-on to a previous laboratory investigation, under Contract DA-27-021-AMC-34 (X), directed at developing lightweight sulfur foams. In that study foams with densities as low as 10 lb/ft$^3$ were prepared consistently in small laboratory equipment. These foams exhibited good thermal and structural properties warranting further investigation, particularly for cold region applications. The object of the current study was to scale up the foam production capability from that of small laboratory equipment, approximately 4 lb per batch, to as much as 500 lb of foam per batch. Once this was accomplished, evaluation of the field placement of rigid sulfur foams for various structural applications was undertaken. One specific application investigated was the preparation of foam core panels, using a variety of skin materials including plywood, polyvinyl chloride, and glass fiber matting. A second area investigated was the use of sulfur foam as a subbase material for roadways. The final application was foamed-in-place shelters, using inflatable forms.

## SCALE-UP FROM LABORATORY EQUIPMENT

The moving of any process from small laboratory equipment to larger equipment involves not only equipment scale-up but often optimization of the operating conditions such as reaction temperatures, mixing times, etc. In the laboratory equipment, sulfur foams had to be prepared at temperatures between 300 and 320F. The maximum working steam pressure for the 100-gal vessel used, however, limited the temperature to 290F. For this reason it became necessary to prepare the foams at a temperature of 290F to evaluate the effect of the time-temperature history upon the foam formulation.

### Time-temperature effect upon reaction

An evaluation of the effect of temperature and time upon the reaction between the various components of the sulfur foams was conducted in the laboratory. Various sulfur formulations were run wherein the reaction temperature was very carefully controlled at 290F. It was found that the foam prepared at these temperatures was very similar to that prepared at the higher temperatures, indicating that no major modifications would be required for either the foam formulation of the proposed pressure vessel.

**Equipment scale-up**

At the same time that the reaction times and temperatures were being investigated in the laboratory, the equipment was also being readied for the production of large batches of sulfur foam. One of the first significant accomplishments of this program was the demonstrated use of a preheated steam hose for discharging foam from the foam generator. In the past, a flexible metal hose has been used, but, in addition to being expensive, these hoses had to be heated by some external source, such as hot gases or electrically traced heaters, to keep the foam molten until deposition. Because of the relatively good insulating characteristics of conventional steam hoses, it was possible to preheat this hose by blowing steam through it and then, once heated, to attach the hose to the foam generator for discharging the sulfur foam. Once the pouring of the foam was completed, this hose was again heated and flushed with steam. This system worked extremely well.

With the equipment in operation, it became possible to study the time-temperature effects upon the sulfur foam in the large equipment. The most important variables to be studied for this scale-up included the reaction time for the various foam components, the mixing time after the addition of the blowing agent, and finally the mixing speed of the agitator. From past experience, it was decided that one variable at a time would be studied. As a result, a systematic approach was undertaken where initially only the time of reaction of the various modifiers to the sulfur was studied. With a constant steam pressure, the reaction temperature could be very carefully controlled.

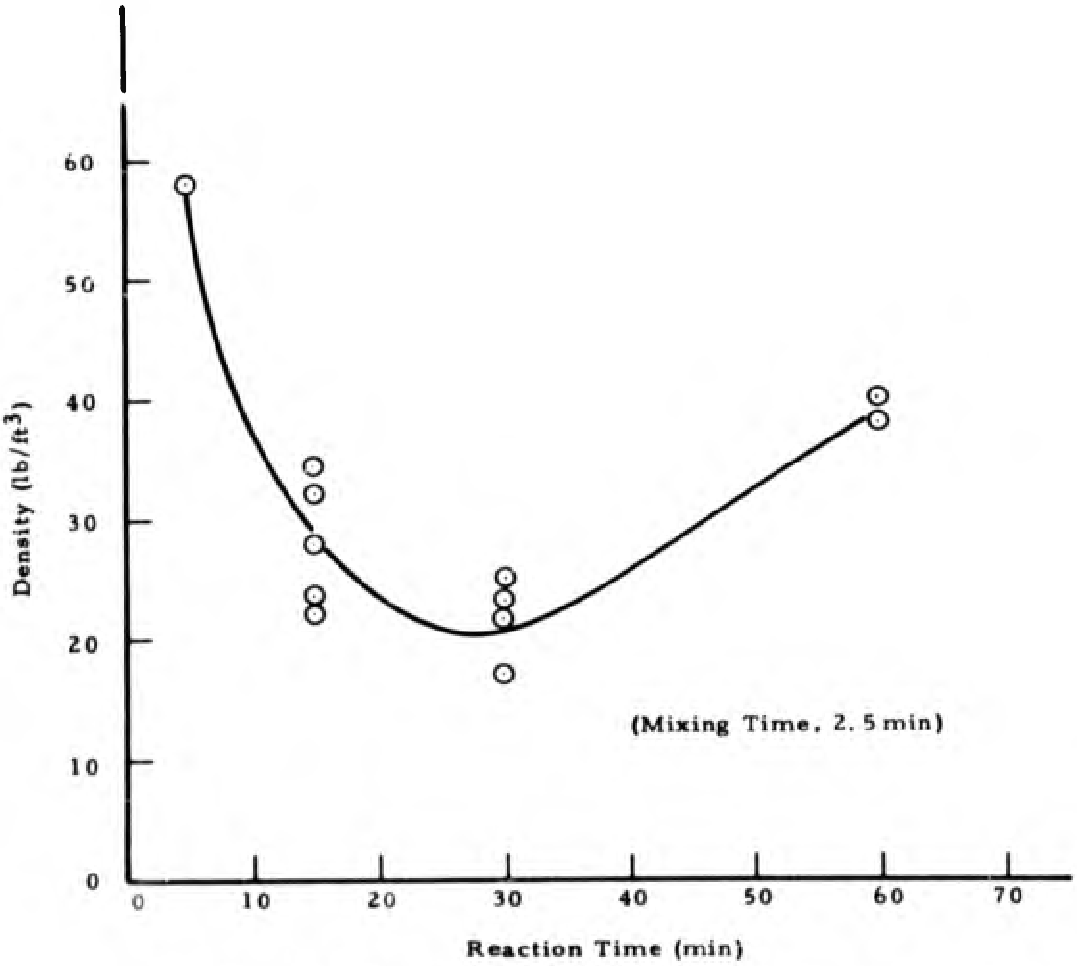


*Figure 1. Density as a function of reaction time.*

The formulation used for all of this initial work was essentially that developed in the previous study:

*Sulfur foam formulation*

| *Component* | *Parts by weight* |
|---|---|
| Sulfur | 100.00 |
| Phosphorus pentasulfide ($P_2S_5$) | 3.00 |
| 1, 5 cyclooctadiene | 3.00 |
| Talc | 10.00 |
| Calcium carbonate ($CaCO_3$) | 3.00 |
| Tricresyl phosphate (TCP) | 0.25 |
| Phosphoric acid ($H_3PO_4$) | 2.60 |

The modifiers that were reacted with the sulfur were the $P_2S_5$ and the 1, 5 cyclooctadiene. The general procedure followed was to heat the sulfur to 290F and then add the $P_2S_5$, 1, 5 cyclooctadiene, talc, and $CaCO_3$, and react for a predetermined period of time, referred to as the *reaction time*. Once the reaction was completed, the $H_3PO_4$ and TCP were added and mixed for an additional period of time, termed the *mixing time*. The TCP is the surfactant for the foams, while the $H_3PO_4$, upon reacting with the $CaCO_3$ and $P_2S_5$, causes the generation of gas which, when released to atmospheric pressure, expands the molten material into a foam. Several batches of sulfur foam were prepared wherein the reaction time was varied from 5 min to 1 hr. The results of these experiments are plotted in Figure 1. From these data, it appeared that an optimum reaction time of approximately 15 to 30 min was required in the large vessel. The next operating variable studied was the mixing time or the length of time that the $H_3PO_4$ and the TCP were agitated with the formulation prior to discharge from the foam generator. The mixing time was varied from ½ to 30 min. It became apparent that the optimum mixing time fell between 1 and 5 min. Times shorter than this would not give adequate mixing, whereas longer mixing times appeared to produce higher density foams. These data are reported in Figure 2.

It also became important to evaluate the effect of the mixer speed upon the quality of the foam produced. Limitations upon the gearbox and pulley systems restricted the range over which the agitator speed could be studied. The agitator speed was doubled from 100 to 200 rpm, but very little improvement was attained. Supplemental investigations were performed by varying the mixer speed in the laboratory equipment. No noticeable improvement was attained in this equipment when the speed was varied over the range of 100 to 1000 rpm. Thus, after studying the variables of reaction time, mixing time, and mixer speed, initial efforts to produce a lightweight sulfur foam resulted in densities of approximately 20 $lb/ft^3$, a factor of 2 above that of the 10 $lb/ft^3$ which was easily obtainable in the laboratory-size equipment.

At that point in the program, a critique of the total findings was undertaken in an effort to determine what major factor may have been overlooked in scale-up of the process. Because of the difficulty in duplicating the quality of foam from batch to batch in the large generator, it was concluded that the formulation would be carefully scrutinized in the laboratory to determine what was necessary in order to give a more stable formulation. It had been known for some time that water was an extremely poor blowing agent for sulfur foams, and yet the reaction between the $H_3PO_4$ and $CaCO_3$ yielded water as one component of the blowing agent. It was also suspected that the acid in contact with other ingredients in the formulation, particularly the $P_2S_5$, caused the generation of gases other than those of the $CaCO_3$ decomposition. An experiment was conducted in the laboratory wherein the $CaCO_3$ was eliminated and the rest of the ingredients were used as normal. The exact formulation used was:

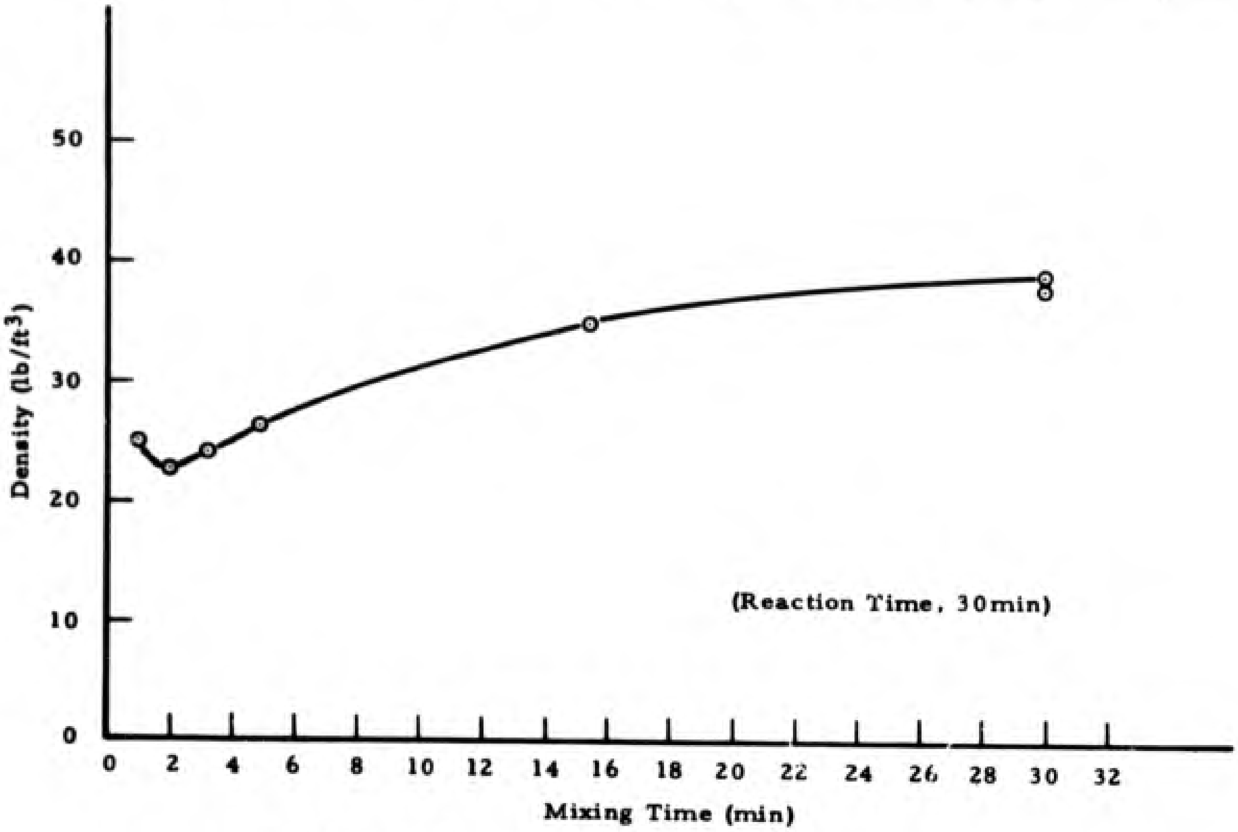


*Figure 2. Density as a function of mixing time.*

| *Component* | *Parts by weight* |
|---|---|
| Sulfur | 100.00 |
| Talc | 10.00 |
| $P_2S_5$ | 3.00 |
| 1, 5 cyclooctadiene | 3.00 |
| TCP | 0.25 |
| $H_3PO_4$ | 3.00 |

This formulation yielded a foam with 12-lb/ft$^3$ density. Further investigations showed that it was the $H_3PO_4$ reacting with the $P_2S_5$ that was producing the gases that acted as the blowing agent. As a result, this identical formulation was used in the large foam generator, and core densities as low as 15 lb/ft$^3$ were realized. Also the quality of the foam was drastically improved, as far as cell size and uniformity is concerned. In subsequent batches prepared in this generator, difficulty was still encountered in duplicating the quality from batch to batch. Observations on the foams produced with the new formulation indicated that lower densities should have been attained by merely increasing the amount of blowing agent. Attempts to increase the $P_2S_5$ and $H_3PO_4$, however, did not yield any lower density foams. It was decided that the problem might well be mechanical, and so a closer look at the reactor vessel itself was undertaken. The vessel, which had been converted, originally had a bonnet valve which sealed in the bottom of the vessel. The stem of the valve itself restricted the exit line, and it was thought that this restriction might be causing the foam to expand when leaving this constricted area into the open full-size line further downstream. It was decided that the valve stem would be removed, thus allowing for a full 2-in. unrestricted discharge line to the valve where the flexible discharge hose was to be connected. It was also decided that the 1-in. valve at this point would be replaced with a 2-in. valve. During removal of the valve, a stone approximately 1½-in. in diameter was found lodged in the valve, thus drastically restricting the foam discharge. With the subsequent installation of the 2-in. valve, and the removal of the old valve stem, it was possible to produce foams in the desired density range with good uniformity from batch to batch. In order to attain foams with densities as low as 10 lb/ft³, the quantity of $H_3PO_4$ and $P_2S_5$ was increased slightly. The formulation used was:

| *Component* | *Parts by weight* |
|---|---|
| Sulfur | 100.00 |
| Talc | 10.00 |
| $P_2S_5$ | 5.00 |
| 1, 5 cyclooctadiene | 3.00 |
| TCP | 0.25 |
| $H_3PO_4$ | 5.00 |

Although run-of-the-mine sulfur is a high purity material as purchased, the experience with the stone lodged in the valve is characteristic of the contamination resulting from the handling and storage. Therefore, molten sulfur should be screened in order to prevent the accumulation of foreign objects in the equipment.

## PRODUCTION OF PANELS, SUBBASES, AND STRUCTURES

With the ability to produce lightweight sulfur foams, it was possible to concentrate on fabricating foam core panels, foam subbases for roadways and buildings, and foamed-in-place structures.

### Panels

Plywood, cloth-backed vinyl, and glass fiber mats were selected for skin materials for the foam core panels. The skin materials were placed inside molds and the sulfur foam was deposited between the two skins. After the foam had solidified, the panels were removed from the mold. The bonding to the plywood, to the cloth-backed vinyl, and to the glass fiber mats was excellent. Panels 2 in. × 2 ft × 6 ft are shown in Figure 3a. The coefficients of thermal expansion for these materials are given in Table I. The bonding to the plywood was enhanced by roughing the plywood surface at the plywood/foam interface. To further determine the bonding characteristics of the sulfur to the skin materials, panels approximately 18 in. × 18 in. were cycled between 30 and 140F. After 20 cycles, the specimens were evaluated, and it was found that the bond at the foam/skin interface was still intact and appeared to be excellent. These panels are shown in Figure 3b with the various skin materials. The only old skin that presented problems was the plywood, which warped when subjected to the thermal cycling and caused the foam to rupture in the center of the panel

**Table I. Coefficient of thermal expansion data.**

| *Material* | *Coefficient of expansion ($10^{-6}$/°F)* |
|---|---|
| PVC | 28-33 |
| Urea-formaldehyde | 12-15 |
| Sulfur | 35 |
| Polyester | 39-56 |
| Polystyrene | 33-48 |
| Polystyrene foam | 35 |

*a. PVC glass fiber and plywood skins.* *b. Test panels with various skin materials.*

*Figure 3. Foam core panels.*

rather than at the foam/skin interface. No difficulty was encountered with the larger panels (up to 8 ft in length) with shearing at the wall/foam interface due to variations in the ambient temperature.

One additional concept that was investigated was preparation of a skin material by the simultaneous spraying of chopped glass fibers and a modified sulfur formulation. This combination was sprayed onto sheet metal. The sulfur was modified with 3% of Thiokol Corporation's ZL507 plasticizer. Once solidified, the skin was placed into the molds and the sulfur foam deposited between the skins as before. Excellent bonding to the foam was achieved, and no problems were encountered with large specimens for fluctuating ambient conditions. The principal disadvantage with the skins prepared in this manner was the weight of the skins. A panel 3 in. × 2 ft × 8 ft weighed 112 lb as compared to 50 lb for a similar panel without skins. With improvements in the spraying techniques, a reduction in the skin thickness would result in a reduction of the weight.

Several techniques were investigated for shaping and trimming the sulfur foam panels. A handsaw as well as a band saw were used on panels with and without the various skin materials and both worked very well. The hot wire technique was investigated for shaping and cutting panels without the skin. While this technique did work, sawing is the recommended procedure at this time.

### Subbase

One promising potential for lightweight sulfur foams is as a subbase material for roadways, airstrips, and buildings in the cold regions of the world. In such applications, the sulfur foam would be covered with a base course aggregate before being topped with portland cement or asphaltic

b.

c.

d.

*Figure 4. Preparation and testing of the sulfur foam subbase.*

concrete. For preliminary screening, foams having core densities of 10 lb/ft$^3$ and 15 lb/ft$^3$ were covered with various thicknesses of fine and coarse aggregates and subjected to sixteen passes of an automobile with wheel loads of 1000 lb. From this preliminary screening, it was found that the 10-lb/ft$^3$ foam required an overlay of 6 in. of a coarse aggregate (½-in. maximum size aggregate) or approximately 1 ft of a fine aggregate (¼-in. maximum size aggregate. A foam subbase 6 in. × 8 ft × 10 ft was then prepared. A series of photographs showing the preparation and testing of the pad is shown in Figure 4. The overall density of this foam pad was 15 lb/ft$^3$. This was somewhat denser than was desired; however, the heat sink effect of the ground caused a faster solidification of the bottom layers of the foam and contributed to the higher overall density. Half of the surface area of this pad was covered with approximately 1 in. of a fine mortar sand to determine its effect as a cushioning medium. The sieve analysis of the specially graded coarse aggregate was very similar to the gradation recommended in Department of the Army Technical Manual TM5-250 "Roads and Airfields," 1957, for use in areas where resistance to detrimental effects of frost action is of special importance. The gradations of the test aggregate and acceptable material are compared in Appendix A. The aggregate was packed by hand and was then subjected to twenty passes with a 4000-lb automobile. The aggregate and sand were removed in selected areas

*Figure 5. Flow of sulfur foam on near vertical wall.*

from the pad, and there was no apparent damage caused by the 1000-lb wheel load. The aggregate was restored above the pad, was again packed by hand, and 20 passes were then made with a Clark Model # CHY120, weighing 18,000 lb gross. This forklift had a weight distribution of 9000 lb on the rear axle and 9000 lb on the front axle. The four front wheels each had a tireprint of 80 $\text{in.}^2$ and exerted a pressure of 28 psi. Each of the two rear wheels had a tireprint of 107 $\text{in.}^2$ and exerted a tireprint pressure of 42 psi. An impression of the tireprint for a rear wheel is presented in Appendix B. During the testing, one of the single rear wheels passed directly over the edge of the foam subbase, causing considerable compaction of the aggregate. This rutting can be seen in Figure 4c. Upon removal of all of the aggregate, inspection of the subbase revealed that the edge over which the single rear wheel had passed caused minor crushing to occur (Fig. 4d). In removing the aggregate a front-end loader accidentally scraped against the front edge of the foam pad and this caused the cracking which is obvious in Figure 4d. From the inspection, it appeared that the 1-in. cushion of mortar sand for the base course aggregate was not really required.

The pad of sulfur foam was prepared by standing wooden forms on edge and making a form having inside dimensions of 6 in. × 8 ft × 10 ft. Before the aggregate overlay was applied to the foam subbase, the wooden forms were stripped away. Although some of the base course aggregate was also applied against the side of the foam base, there was not enough support, and, when the single rear wheel passed directly over the edge, the pad not being constrained at the edge had a tendency to fail. Had this foam been poured in an excavation as would be the case in actual practice, it is doubtful if damage would have occurred along the edges.

*Figure 6. Small structure supporting a load.*

**Fabrication of a small structure**

One of the principal advantages that sulfur foam holds for Arctic construction is that rigidization of the sulfur foam depends strictly on heat loss for a phase change. This is an important consideration because of the low ambient temperature conditions experienced in the Arctic, which are usually detrimental to the reactions required for organic foams for poured-in-place applications. In order to evaluate the concept of preparing poured-in-place structures, truck innertubes approximately 4 ft in diameter were used by placing then side by side when inflated, such that an arch type structure is obtained when glass mat is draped over the innertubes. Initial attempts using a 2 oz/ft$^2$ chopped strand glass mat failed because the sulfur foam, although expanded, was still liquid and would flow from the near vertical surface as is shown in Figure 5. One attempt to overcome this problem was simply to place the glass mat on the ground and deposit the foam over the mat, which then expanded and rigidized in a 2-in. thickness. The walls for the structure were cut from this mass of foam and placed against the sides of the innertubes. Sulfur foam was then poured-in-place as the roof of the structure and, upon coming in contact with the solidified walls, welded itself into an integral unit. The structure fabricated in this manner had a wall and roof thickness of approximately 2 in. and was strong enough to support a man weighing 190 lb (Fig. 6).

The most promising technique, however, for preparing the prototype poured-in-place structures was achieved by using a 2 oz/ft$^2$ expanded glass mat which is used primarily as an air filter medium. When this mat was draped completely over the 4-ft innertubes, the sulfur foam could be

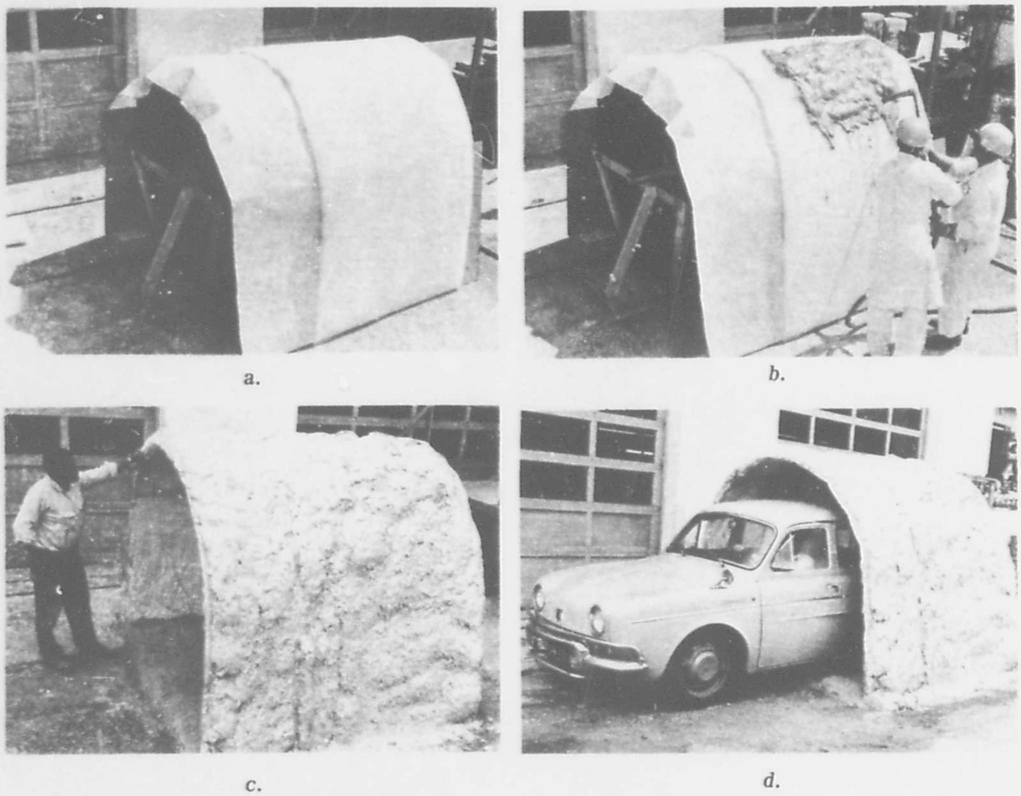


*Figure 7. Fabrication of a large structure.*

blown into the mat which then expanded to between 2 and 3 in. thick. The random pattern of the glass fibers within the mat prevented the flow of the foam and gave sufficient strength to prevent the mat from tearing. Hence, there was very little drainage of the foam from the walls, and a rather uniform wall thickness was attained in this manner.

**Fabrication of a large prototype structure**

In order to fabricate a larger structure using the poured-in-place method with the sulfur foam and the 2-in.-thick expanded air filter medium, four large aircraft innertubes were obtained. When fully expanded, these innertubes had a diameter of approximately 7 ft, with a width of approximately 2 ft. A wooden frame structure was fabricated to hold these four innertubes side by side, which gave a form approximately 7 ft high, 7 ft wide, and 8 ft in length. A 4 × 8-ft sheet of plywood was then placed along each side of the structure to support the walls from the horizontal diameter to the ground. Glass matting with a density of 1 oz/ft$^2$ was first draped over the innertubes and the plywood boards. This matting acted as a barrier to the sulfur foam, preventing it from contacting the plywood form and the innertubes. It also provided a smooth interior surface for the structure, which could then be sprayed with a plasticized sulfur formulation to give a smooth, finished, esthetic surface. Over this was draped the 2-in.-thick expanded air filter medium glass mat. Sulfur foam was sprayed into the expanded glass mat starting at the crown of the structure and working down on each side of the structure. A series of photographs showing the fabrication of this structure is presented in Figure 7. Two batches, approximately 720 lb, of foam were required to

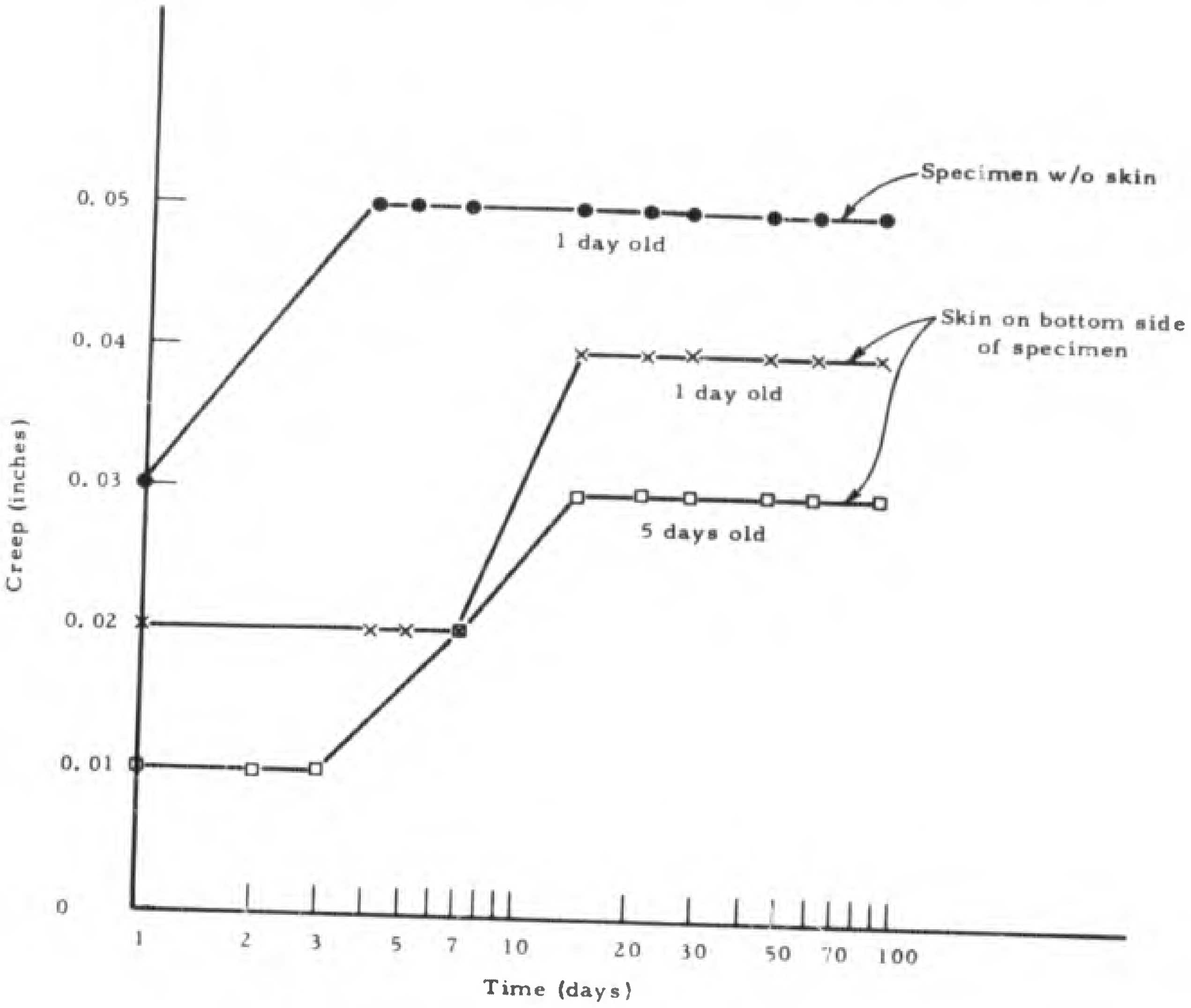


*Figure 8. Creep characteristics of sulfur foams.*

complete this structure. Since the air filter medium mat was only 5 ft wide, a joint was made by simply overlapping two sections of this mat about 6 in. This material bonded extremely well, and it is difficult to tell where the joint was made. Again, very little drainage of the foam from the steep walls was encountered by using this glass mat.

The form supported the structure for approximately 15 hr before it was collapsed and pulled out from beneath the structure. It was envisioned that additions could be made to this structure by simply moving the form forward, adding more glass matting, and tying into the structure.

After several days of observation of this structure, it was planned to finish the interior with a plasticized sulfur formulation, and the structure was then to have been uniformly loaded with sandbags. Unfortunately, the structure failed after standing unsupported for 5 days. Since the failure occurred on a weekend, the failure in progress was not observed. From the appearance of the failed structure, however, it would seem that the structure failed first along the centerline at the top of the arch. The roof collapsed, causing a secondary failure to occur at the walls at approximately a 45° angle from the centerline of the floor such that the failed structure formed an M cross section. The collapse of this structure was unexpected, particularly in view of the fact that the smaller 4-ft structure showed absolutely no signs of failure even after several months of exposure.

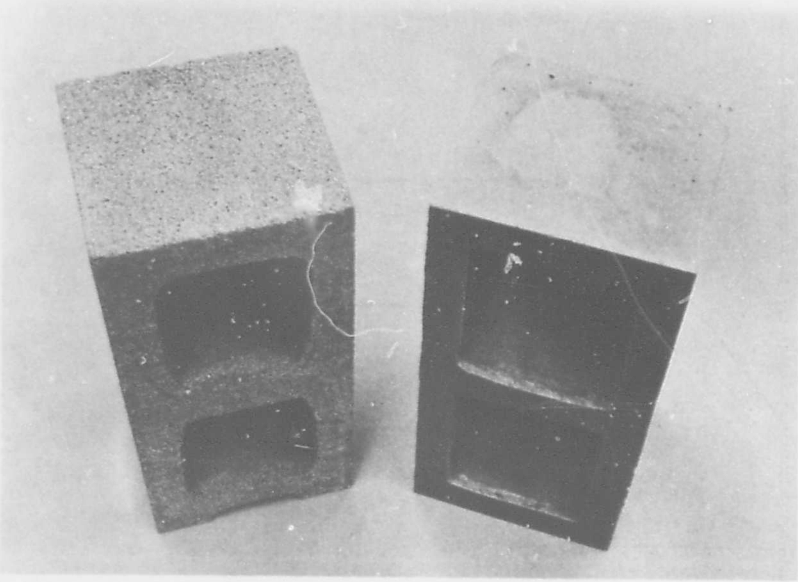


*Figure 9. Sulfur foam block (right) compared with conventional lightweight concrete block (left).*

As a result, evaluation of the creep properties of the sulfur foam was undertaken. Specimens 1 and 5 days old were subjected to creep determinations by measuring the creep on nonloaded flexural specimens. Specimens 1 × 6 × 9 in. were supported on 8-in. centers, and the creep in the center point of the specimens was measured. These creep determinations were run for a total of 3 months; the results are shown in Figure 8. From these data, it was ascertained that the sulfur foam undergoes an initial creep before finally stabilizing. Thus, it would appear that before sulfur foam can be used for poured-in-place structures, foam formulations and structure design studies will be required to minimize the effect of the initial creep characteristics.

One area of investigation which was recently conducted for the Aero Propulsion Laboratory under Air Force Contract F 33615-67-C-1932 was the production of sulfur foam blocks similar in size and shape to lightweight concrete blocks. This work was done with the cognizance of the contracting officers and project monitors, and with the agreement that the results would be presented in this report as well as in Technical Report AFAPL-TR-68-96. Figure 9 shows a sulfur foam block compared with a conventional lightweight concrete block. The concrete block on the left weighs 30 lb as compared to 6 lb for the sulfur foam block on the right.

**Physical and mechanical properties of sulfur foam**

The water vapor transmission of the sulfur foams was determined in accordance with ASTM C-355-64 (*Water Vapor Transmission of Thick Materials*). These tests were conducted at an average room temperature of 70F and 40% relative humidity. After 1 month of exposure, these foams were found to have a water vapor transmission, permeance, and permeability of zero.

The mechanical properties of the sulfur foam were determined under Air Force Contract F 33615-67-C-1932 and are reported here in accordance with the agreement.

The mechanical properties were determined as soon as 1 hr after solidification and again after 7 days. One 200-lb batch of foam was generated, and all specimens were prepared and tested from this batch. The formulation used had the following composition:

| *Component* | *Parts by weight* |
|---|---|
| Sulfur | 100.00 |
| Talc | 10.00 |
| $P_2S_5$ | 5.00 |
| $H_3PO_4$ | 5.00 |
| 1, 5 cyclooctadiene | 3.00 |
| TCP | 0.25 |

The data are reported in Table II. With the exception of the shear strength, there was a decrease in strength of the foam after 7 days. It is believed that this difference is due to the difference in the property strengths between the monoclinic crystalline form prevalent after 1 hr and the orthorhombic crystalline form prevalent after 7 days. These same characteristics have been determined before with tensile specimens of pure elemental sulfur.

**Table II. Mechanical properties of lightweight sulfur foam.**

(Foam core density 11 lb/ft$^3$.)

| *Property* | *At 1 hr* | *At 7 days* |
|---|---|---|
| Tensile strength | 10 psi | 9 psi |
| Compressive strength | 48 psi | 37 psi |
| Stress-strain characteristics | 48 psi for 60% deformation | 37 psi for 60% deformation |
| Modulus of elasticity | 1420 psi | 1170 psi |
| Flexural strength | 50 psi | 39 psi |
| Shear | 13 lb/in.$^2$ | 16 lb/in.$^2$ |
| Impact | 7 in.-lb | 4 in.-lb |

The tensile strength of the sulfur foam was determined in accordance with ASTM C 496 (*Splitting Tensile Strength of Molded Concrete Cylinders*). All of the specimens characteristically split in half when tested.

The compressive strength was determined by pushing a 10-in.$^2$ plate into a specimen having the sides constrained. This was done to ensure a constant test area at all times during the test. The stress-strain characteristics of the foam were determined from the load-deformation curve as plotted by Instron testing machine when testing the specimens in compression. The modulus of elasticity was calculated from these curves after allowing for the slippage in the equipment. Flexural strength was determined in accordance with ASTM C 78 (*Flexural Strength of Concrete Using Simple Beam with Third-Point Loading*). The specimens were tested with the skin perpendicular to the load, and all failed in the middle section of the specimen as desired. Those specimens tested with the skins parallel to the load were approximately 20% weaker than the others.

The shear strength was determined by punching a core out of the center of a 1-ft$^2$ specimen 3 in. thick. The specimen was placed over a steel plate having a 9-in.-diam hole in its center. On top of the specimen, a 9-in.-diam plate was centered above the hole in the lower plate. The top plate was then loaded in compression, which punched a core out of the center of the specimen.

Impact strength was determined by dropping a 3.33-lb mass in the center of a specimen 3 × 3 × 10 in. The ends were supported 8 in. apart. All specimens broke directly under the point of impact.

## CONCLUSIONS AND RECOMMENDATIONS

The major conclusions drawn as a result of this study are as follows:

1) Sulfur foam with the same attractive physical properties as that prepared in the small laboratory-size equipment can be prepared on a large scale in conventional, large-scale process equipment.

2) These foams are particularly attractive as thermal insulators for subbases for roadways, airstrips, and buildings in the cold regions of the world.

3) These foams also show promise for foam core panels and lightweight blocks for structural applications.

4) Because of the initial creep characteristics of sulfur foam, further investigations are required for its utilization in foamed-in-place structures.

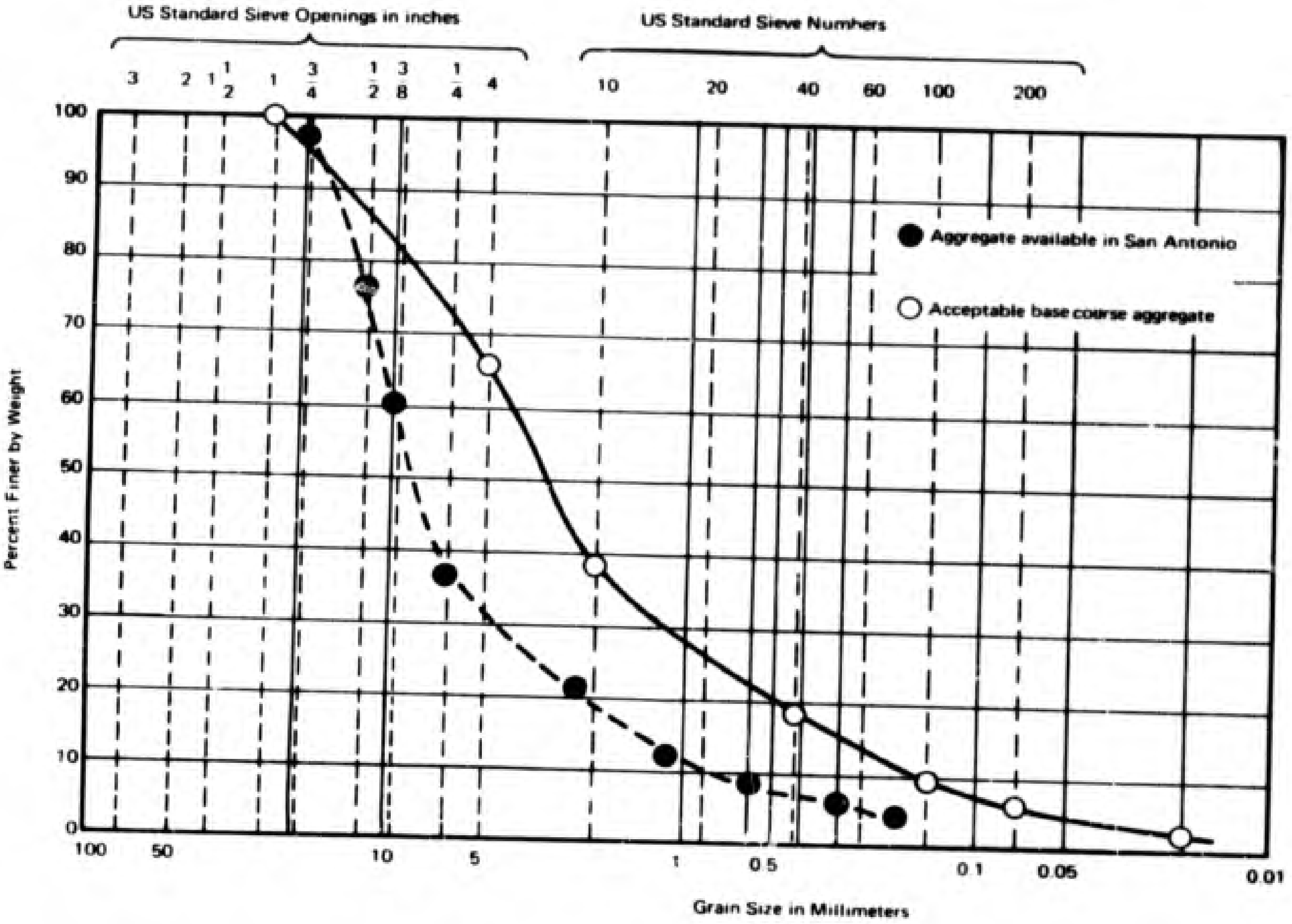
Recommendations:

1) In order to have the capacity for producing the quantities of sulfur foam required for applications such as subbases, a continuous foaming apparatus should be considered wherein the foam formulation is reacted with the phosphoric acid in the discharge line immediately prior to deposition.

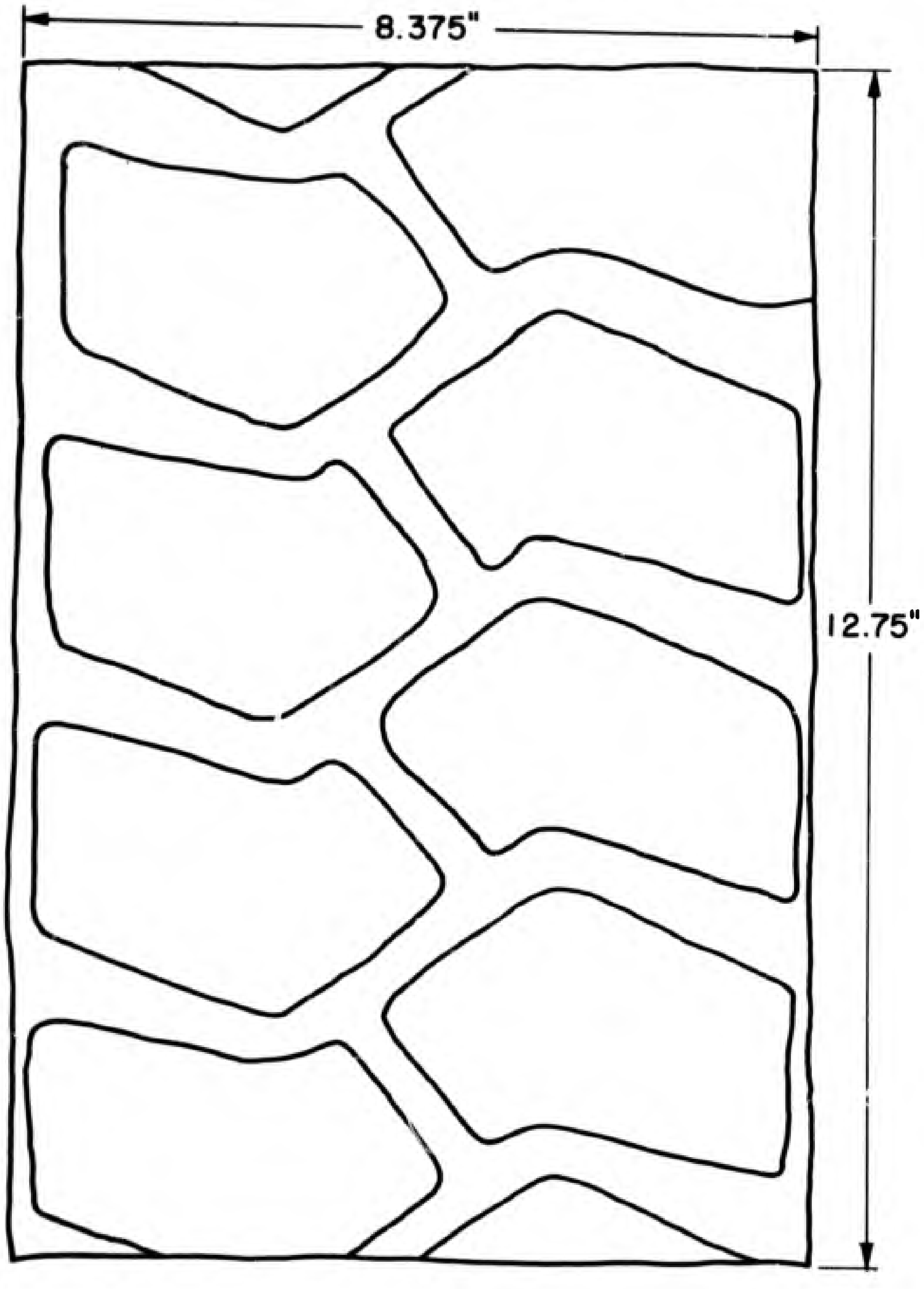
2) Further investigations should be devoted to developing construction techniques employing the foam block as well as the foam core panel concepts.

3) In order to employ sulfur foam for foamed-in-place structures, formulation studies should be undertaken to minimize the initial creep characteristics. Closely allied with this would be the design of structures which could minimize the effect of these initial creep characteristics.

# APPENDIX A: SIEVE ANALYSIS OF BASE COURSE AGGREGATE



## APPENDIX B: TIREPRINT OF REAR WHEEL OF FORKLIFT



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11. SUPPLEMENTARY NOTES

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13. ABSTRACT

Previous studies indicated that lightweight sulfur foams had thermal insulating characteristics and mechanical properties which were sufficiently attractive that they could be considered for a number of structural applications. The subject study was undertaken in order to determine if the process for preparing sulfur foam could be scaled up from small laboratory-size equipment, producing 4 lb of foam per batch, to large conventional pressure-heated equipment capable of producing 500 lb of foam per batch. This was accomplished, and large quantities of sulfur foam were prepared and tested for such applications as subbases for roadways, as foam core panels, and for foamed-in-place structures. The sulfur foams appear particularly attractive for the subbase applications and foam core panels. Further investigations are required for the foamed-in-place structures because of the initial creep characteristics associated with the sulfur foams, first identified during the course of this study.

14. KEY WORDS

Buildings
Foaming
Foam panels
Foundations
Insulation
Subgrades
Sulfur foam

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