MISCELLANEOUS PAPER NO. 6-973

PROJECT BIG PAPA - PHASE III CELLULAR CONCRETE FRAGMENTATION ACCEPTORS

by

G. C. Hoff
W. F. McCleese
A. A. Bombich

February 1968

Sponsored by

Air Force Weapons Laboratory

Conducted by

U. S. Army Engineer Waterways Experiment Station
CORPS OF ENGINEERS
Vicksburg, Mississippi

[illegible]

MISCELLANEOUS PAPER NO. 6-973

PROJECT BIG PAPA - PHASE III CELLULAR CONCRETE FRAGMENTATION ACCEPTORS

by

G. C. Hoff

W. F. McCleese

A. A. Bombich

COLOR ILLUSTRATIONS REPRODUCED IN BLACK AND WHITE

February 1968

Details of illustrations in this document may be better studied on microfiche

Sponsored by

Air Force Weapons Laboratory

Conducted by

U. S. Army Engineer Waterways Experiment Station

CORPS OF ENGINEERS

Vicksburg, Mississippi

ARMY-MRC VICKSBURG, MISS.

FOREWORD

The BIG PAPA, Phase III, program involved many subprograms. The material contained in this report is the result of one of those subprograms. No attempt is made to describe or discuss any other aspects of the BIG PAPA program. This research investigation was sponsored by the Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico, and coordinated with the Air Force Office of Civil Engineering, Washington, D. C.

The investigation was conducted both at the Concrete Division, U. S. Army Engineer Waterways Experiment Station (WES) and the Hill Air Force Base Test Range, Lakeside, Utah, during the period of June 1967 to October 1967. The work was accomplished under the general supervision of Mr. Bryant Mather, Chief of the Concrete Division, and Mr. James M. Polatty, Chief of the Engineering Mechanics Branch, Concrete Division. The theoretical considerations and laboratory work were provided by Mr. Anthony A. Bombich of the Engineering Physics Section, Engineering Mechanics Branch. The materials work and field inspection and supervision were provided by SP4 William F. McCleese and Mr. George C. Hoff of the Concrete and Rock Properties Section, Engineering Mechanics Branch. This report was prepared by Mr. Hoff under the direct supervision of Mr. William O. Tynes, Chief of the Concrete and Rock Properties Section.

Director of WES during this investigation was COL John R. Oswalt, Jr., CE. Mr. J. B. Tiffany was Technical Director.

Preceding page blank

CONTENTS

Preceding page blank

NOTATION

d_p	Depth of penetration
h	Total thickness of acceptor material
KE	Kinetic energy
m, m_1	Mass
V, V_1	Velocity
U_p	Plastic energy (nonrecoverable)
U_t	Total energy
ϵ	Strain (unit deformation)
ϵ_y	Yield strain (yield deformation)
$\epsilon_{0.40}$	Forty percent deformation
σ	Stress
σ_y	Yield stress
$\bar{\sigma}_{0.40}$	Average stress to 40 percent deformation
$\sigma_{0.40}$	Stress at 40 percent deformation

Conversion Factors, British to Metric Units of Measurement

British units of measurement used in this report can be converted to metric units as follows:

Multiply	By	To Obtain
inches	2.54	centimeters
feet	0.3048	meters
square inches	6.4516	square centimeters
cubic feet	0.0283168	cubic meters
gallons	3.78533	liters
pounds	0.45359237	kilograms
pounds per square inch	0.070307	kilograms per square centimeter
pounds per square foot	4.88243	kilograms per square meter
foot-pounds	0.138255	meter-kilograms

Preceding page blank

SUMMARY

The objectives of this study were to determine the feasibility of using cellular concrete as a fragment-catching mechanism for acceptor blocks and, if feasible, to provide laboratory and field support for the design, calibration, inspection, and postshot evaluation of cellular concrete to be used in ten acceptor blocks subjected to fragments and barrier spalls from a munitions explosion.

A limited study involving three test shots with the WES air gun and a standard cylindrical shaped projectile traveling at different velocities into a block of cellular concrete indicated that the cellular concrete would accommodate fragments and barrier spalls by a predominately plastic failure with little or no rebound, cracking, and splitting. The results of these shots also indicate that it is possible to calibrate a mixture proportion for cellular concrete with respect to a given projectile shape, mass, velocity, and orientation.

Supervision and inspection of the field placing of 740 cu yd of cellular concrete for ten acceptor blocks were provided. Due to severe damage inflicted to the blocks by the explosion and accompanying crater and ejecta, no useful information was obtained from a postshot inspection. Sixteen strength control cylinders were evaluated and are analyzed along with the quality control unit weight checks made during placing. The specifications for the cellular concrete acceptor blocks are contained in the appendix to this report.

Preceding page blank

PROJECT BIG PAPA - PHASE III
CELLULAR CONCRETE FRAGMENTATION ACCEPTORS

PART I: INTRODUCTION

Background

1. In November 1961 an investigation entitled "Shock-Absorbing Materials" was begun at WES to evaluate and develop materials which could be used around deeply buried protective structures and missile silos to absorb ground motions, dissipate shock energy, and transmit particular design stress levels to the structures. The results of the initial studies of that investigation[1] indicated that low-density concretes were satisfactory for that purpose and that they were also relatively easy to handle and place and economically attractive. Of the types of low-density concretes investigated, cellular concrete, or "foamed" concrete, as it is often called, appeared to have a slight advantage over the other types when considered for use in remote construction areas as the foamed concrete required only air as aggregate and thus eliminated low-density aggregate transportation and handling problems associated with the other types of low-density concretes.[2] The physical properties and characteristics of cellular concretes with respect to this type of application are reported in reference 3.

2. In March 1965 construction of a tunnel complex using cellular concrete as a shock-absorbing backpacking material was begun and continued

for approximately 14 months. This construction resulted in the placing of approximately 19,000 cu yd of cellular concrete designed for a number of different densities and strengths[4] at an in-place cost of $12.50 per cu yd of cellular concrete.

3. Concurrently with the above field program, a laboratory study entitled "Investigation of Wall Construction Techniques to Attenuate Blast Effects from High-Explosive Detonations" was designed and finally initiated in November 1965. The objective of this study (which is still continuing) is to investigate methods of attenuating the blast effects of accidental detonations in facilities for the manufacture, assembly, maintenance, and storage of high explosives, munitions, and high-energy propellants. In the case of explosive materials situated in adjacent areas, the problem of propagation from one lot to another is being studied as it has been clearly established that high-velocity fragments are a principal mechanism of propagation. These may be "primary" fragments from munitions and/or the materials encasing or adjacent to the explosives and/or "secondary" fragments produced by breakup or spalling of barriers separating the donor and acceptor explosives. Initial test results[5,6] indicate that cellular concrete when used in sandwich-type wall construction is effective in reducing peak stresses in the wall and in reducing the spall potential of the wall.

4. In all of the above studies involving cellular concretes, many compression tests were made on constrained samples of cellular concrete

for both slow and rapid rates of straining. In most instances this test consisted of uniaxially loading the surface of a 6-in.-diameter by 6-in.-high constrained cylinder with a 4-in.-diameter loading piston. The resulting test was a combination of compression and, once the sample reached its crushing stress, punching shear. These tests, regardless of the strain rate, demonstrated the ability of cellular concrete to absorb the energy and displacements caused by a moving piston or projectile without disintegrating the concrete and with negligible rebounds.

5. In June 1967, at the request of the U. S. Air Force (AFOCE-KC), the WES initiated an investigation that would utilize its extensive background with cellular concrete and evaluate the fragment energy transmitted from munitions explosions and barricade spalls to simulated acceptors. These acceptors were to be made of cellular concrete. This report contains the results of that evaluation.

Purpose and Scope of Investigation

6. The purposes of this investigation were to:

a. Determine the feasibility of using cellular concrete as a fragment-catching mechanism for acceptor blocks.

b. In the laboratory, calibrate cellular concrete as a fragment-catching mechanism.

c. Provide all cellular concrete mixture proportions to be used in the field test portion of BIG PAPA, Phase III.

d. Provide guidance and help to the contractor performing the cellular-concrete field placement with regard to equipment, materials, mixing, handling, and placing.

e. Provide inspection of all cellular concrete during placement, including all adjustments of mixture proportions, sampling, and testing.

f. Provide postshot inspection and evaluation of all acceptor pads to include plotting fragment locations, angles, depth of penetration, and fragment retrieval.

g. Experimentally determine the depth of penetration versus fragment energy for idealized shapes representing the actual fragments retrieved and relate this information to the observed penetrations in the field.

7. A limited study involving three test shots with the WES air gun was done to determine the feasibility of using cellular concrete as an acceptor and also to roughly calibrate some cellular concrete made with the same mixture proportions as the concrete proposed to be used in the field phase. Supervision and inspection of the field placing of the cellular concrete was provided for ten acceptor blocks constructed at the Hill Air Force Base Test Range, Lakeside, Utah. Approximately 740 cu yd of cellular concrete were placed. Due to severe damage inflicted to the blocks by the explosion and accompanying crater and ejecta, it was impossible to conduct any of the proposed postshot work.

PART II: THEORETICAL CONSIDERATIONS

8. The principal purpose of this study is to determine the kinetic energy of munitions fragments and barrier spalls at the moment of contact of these missiles with the surface of the acceptor pads. Classically, the kinetic energy is expressed as:

$$KE = 1/2\ mV^2 \tag{1}$$

where

m = mass of the fragment

V = velocity of the fragment

9. Consider first a projectile of mass, m_1, moving along a constant path with a constant velocity, V_1, and uniform orientation. The projectile is flat-ended with a unit end area and a uniform cross section. Neglect, for the moment, all other factors that may affect the behavior of this projectile in flight. At the moment the flat-end unit area makes contact with an acceptor surface, the projectile will have a kinetic energy equal to $1/2\ m_1\ V_1^2$. If the acceptor material is uniform, homogeneous, and has a constrained stress-deformation characteristic such as that shown in plate 1, the depth of penetration of the projectile into the acceptor can readily be determined. The amount of energy dissipated per unit volume of acceptor material is equal to

$$U_t = \int_0^{\epsilon} \sigma \cdot d\epsilon \tag{2}$$

where

U_t = total energy dissipated, in.-lb/cu in.

σ = stress in the material, psi

ϵ = total unit deformation in the material under the loaded area, in./in.

Simply, U_t is equal to the area under the stress-deformation curve to a given unit deformation, ϵ. For the penetration problem, U_t will be equal to KE, hence

$$1/2\ m_1 V_1^{\ 2} = \int_0^{\epsilon} \sigma \cdot d\epsilon \tag{3}$$

or for a unit end area of projectile

$$1/2\ mV^2 = \bar{\sigma} \cdot \epsilon \tag{4}$$

where $\bar{\sigma}$ = average stress in the material to unit deformation, ϵ, psi. In terms of the unit deformation

$$\epsilon = \frac{m_1 V_1^{\ 2}}{2\bar{\sigma}} \tag{5}$$

or

$$\epsilon = \frac{d_p}{h} \tag{6}$$

where

d_p = depth of penetration, in.

h = total thickness of acceptor material, in.

The depth of penetration is then equal to

$$d_p = \frac{m_1 V_1^{\ 2}\ h}{2\bar{\sigma}} \tag{7}$$

10. In the laboratory, the idealized projectile described above can be used on acceptor materials of known stress-deformation characteristics

and, knowing the mass and impact velocity of the projectile, the depth of penetration can both be calculated and measured. In the field, however, the impact velocity is not known. The stress-deformation characteristics of the acceptor material can be determined; and, after penetration by the projectile, the depth of penetration can be measured and the projectile retrieved and its mass determined. From this information, the impact velocity can be calculated as

$$V_1 = \sqrt{\frac{2\ d_p\ \bar{\sigma}}{m_1\ h}} \tag{8}$$

and from equation 1, the kinetic energy of the projectile determined.

11. There are other factors not considered in equation 8 which affect the depth of penetration of a fragment; in general, however, equation 8 can be used to obtain a rough approximation of the kinetic energy. Other factors which affect the depth of penetration are: the shape of the fragment, the orientation of irregular shapes, the surface areas presented to the acceptor material during penetration, and the loading rate. A needle- or bullet-shaped fragment of a given mass and velocity can be expected to penetrate further than a disc-shaped fragment of the same mass and velocity impacting on its flat surface. Since most materials which could be used as acceptors, including the cellular concrete, are strain- and load-rate sensitive,[3] the rate at which the acceptor material is loaded by the fragment will also affect the acceptor's resistance to penetration. Faster rates of loading and straining result in greater $\bar{\sigma}$ values for a particular material and, hence, greater resistance to penetration.

12. Both of the factors just mentioned may contribute some error in the determination of the kinetic energy of a fragment. These factors would be in evidence regardless of the acceptor material used. The effect and magnitude of the error associated with these factors can be determined in the laboratory, however, and then compensated for in the determination of the actual field kinetic energy.

PART III: LABORATORY PHASE

13. A series of three tests was conducted to ascertain the feasibility of using cellular concrete as a fragment-catching mechanism for acceptor blocks and the calibration of depth of penetration versus fragment energy.

Materials

14. A 2-ft cube of cellular concrete was used to simulate a field acceptor. The cellular concrete contained no aggregate or mineral filler but was composed only of cement, water, and air. Type III cement was used. The water-cement ratio (by weight) was 0.65 and the concrete had a unit weight of 43 pcf. The concrete block was evaluated at nine days age and had a cylinder yield strength of 156 psi at that age. The block and the cylinders were cured in the mold 48 hr and then air cured in the laboratory until tested.

Test Apparatus

15. A 2.3-lb cylindrical aluminum projectile was used in all tests. The projectile was fired from a gas gun having a 2-in. bore, 10-ft launch tube, and a pressure chamber designed for 2000 psi. Both the weight of the projectile and the breech pressure can be varied to attain different impact velocities. For these tests, the projectile weight remained constant and the breech pressure was varied. The projectile velocity was determined from a breech pressure-projectile velocity correlation which had been developed for the actual projectile used.

Test Procedures

16. The plane-faced cylindrical projectile was impacted on the cellular concrete block at velocities of 200, 310, and 380 fps. The blocks were unconfined with a semirigid support at the rear surface opposite the impact surface. The depth of projectile penetration was measured with a steel rule.

Test Results

17. The results of the impact tests are shown in table 1. Plate 2 shows the relation between depth of penetration and impact velocity. Photographs 1 and 2 show the actual projectile penetrations into the acceptor block for shots 1 and 2. As shown in these photographs, a clearly defined path of penetration into the cellular concrete exists. No spalling or cracking which would interfere with a depth of penetration measurement is visible around edges.

Discussion of Results

18. As indicated in plate 2, a correlation between depth of penetration and impact velocity for a projectile of a particular size, shape, and orientation can be made. The cellular concrete appears to have negligible amounts of cracking and splitting under impact loads and had predominately plastic failure with little or no rebound. Based on the results of these limited tests then, it can be concluded that cellular concrete has the desired material properties and behavior to be used as a fragment-catching mechanism in the field phase of this study.

PART IV: FIELD PHASE

19. The actual placing of the cellular concrete for the field acceptor pads (fragmentation traps) began on 29 September 1967. A total of ten fragmentation traps was placed over a five-working-day period. The pads were located in an array around a central donor pad and six revetment walls as shown in plate 3. Each trap had both an alphabetic and a mumerical designation as indicated in plate 3. Traps A1, B1, C1, D1, E1, and F1, which immediately surrounded the donor pad and revetment walls, were 30 ft wide by 30 ft long with a 7-ft vertical face. The pads were 2 ft thick for both the horizontal and vertical sections. Plate 4a shows a sketch of one of these traps. All six of these traps were constructed on previously compacted 5-ft earth fills with the front face of the cellular concrete extending to the ground surface. The remaining four traps, A2, A3, D2, and D3, were 30 ft square by 2 ft thick and were constructed on the flat desert floor. Plate 4b shows a typical sketch of this type of trap.

General Construction

20. To avoid repetition, it can be stated that the construction, in general, was in accordance with the job specifications as contained in Appendix A of this report with exceptions that will be noted in the remainder of this text plus supplemental comments that are also included.

Materials

21. Type III cement was used for the entire job. The foaming agent used was a stabilized protein concentrate. The actual mixture proportion used is contained in section 7.3 of the specifications in Appendix A.

Cellular Concrete Fabrication

22. The cellular concrete was batched in 6-cu-yd quantities in ready-mix transit trucks. The cement was used in bulk and was stored in temporary field-storage trucks. The required amount of cement for a 6-cu-yd batch was fed into a weigh-batcher which, in turn, dumped the cement into the trucks as the water was being added (photograph 3). The mixer drum of the truck was operated at its maximum speed during this operation in an attempt to eliminate the balling of cement in the mixer.

23. Once the slurry was mixed, the preformed foam was added. Photograph 4 shows the truck backed up to the foam generating equipment which had been mounted on a pickup truck. The foam solution and discharge rate for the foaming nozzle had been adjusted and regulated so that 55 gal of premixed foam solution would provide the necessary amount of preformed foam for a 6-cu-yd batch. The total discharge time for this amount of foam was 10 minutes. Photograph 5 shows the preformed foam entering the mixing truck. The speed of the mixing drum was greatly reduced during this operation to prevent knocking some of the air out of the foam. Once the foam had been added, the truck was immediately brought to the formwork and the load emptied (photograph 6). Photograph 13 shows the proximity of the batching operation to the formwork.

Formwork

24. Only two types of forming were necessary: the horizontal trap with the vertical face and the horizontal trap without the vertical face. Photograph 7 shows a typical view from the rear of the form of the horizontal portion of the formwork with the vertical face. Photograph 8 shows the inside of the vertical face of that same form. The bracing required for the vertical face is shown in photograph 9. Inadequate bracing will result in form movements which cannot be tolerated as seen in photographs 10 and 11. The cellular concrete had been placed in the vertical face portion to a level as indicated by the concrete of the formwork in photograph 10. The form then moved due to the hydrostatic loading by the concrete and buckled, causing the concrete to flow out from under the form (photograph 11). Photograph 12 shows an overall view of this type of formwork. The typical formwork without the vertical face is shown in photograph 13.

Cellular Concrete Sampling, Placing, and Curing

25. One 6- by 12-in. cylinder was made for any load or portion of a load of concrete that went into a given fragmentation trap form. This resulted in 131 cylinders, which represented 740 cu yd of cellular concrete. These samples were used to check the unit weight of each truck at the time of placing and also for strength determinations on D-day. A summary of the unit weight quality controls for all of the traps is shown in table 2.

26. The fragmentation traps without a vertical face were placed by having the mixing truck unload at each corner of the pad (photograph 6),

rotating in a clockwise manner until the form was filled. Photograph 14 shows a completed trap immediately after placing. A similar trap with the formwork removed is shown in photograph 15.

27. The traps with the vertical face had the vertical portion placed first. After the failure of the formwork during the second placing of a vertical section (photographs 10 and 11), it was decided to place the remaining vertical portions in small lifts and to allow each lift to stiffen before placing an additional lift on top of it. This worked very satisfactorily. By strict interpretation, this technique was not in accordance with section 10.4 of the specifications (Appendix A). The reasoning behind the prohibiting of all cold joints except vertical joints was to allow maximum fragment penetration in the horizontal portion of each trap without a joint affecting the penetration. In the case of the vertical portion of a trap, however, a horizontal joint when referenced to the direction of impact by barrier spalls and fragments could be construed as a vertical joint as it would not affect the penetration. The deviation from the specifications was then considered as acceptable. The only access to each of these traps was from the center rear. The mixing truck unloaded into an independent chute which ran the length of the form to the vertical face. Once the vertical face was completed, a 15-ft chute attached to the mixing truck was used to place the concrete in all corners of the formwork. A completed section, A1, with the formwork still on is shown in photograph 16. Traps A2 and A3 are in the background. Photographs 17 and 18 show a typical finished trap with a vertical face. The cold joints are quite obvious.

28. All exposed sample and trap faces were sprayed with a curing compound shortly after completion of the placing. No other curing aid or treatment was given to any of the concrete.

29. No unusual problems were encountered during the placing operation. Section 10.3 of the specifications (Appendix A) was not enforced due to the brevity of the allowable construction time. The purpose of that requirement in the specifications was to prevent the placing of fresh concrete on top of concrete that had begun its initial and final setting phase. The results of this practice are twofold: (a) the freshly placed concrete from the discharge hole or truck will disturb the concrete in the form which has begun stiffening and cause partial collapse of the air-bubble system in the concrete placed initially, which would result in localized density variations throughout the section, and (b) by placing each trap, with the exception of the vertical faces, in one continuous operation, extremely hot temperatures develop in the concrete mass due to the hydration of the cement. These temperatures can result in some thermal cracking as is shown in photographs 19 and 20. This was expected under the circumstances. The cracking was not expected to affect the penetration, but the excessive heat combined with the free moisture in the concrete produced a crude type of autoclave which undoubtedly affected the strength of the in-situ concrete. The practice of continuously placing large volumes of cellular concrete in thicknesses such as those used in this program for periods of more than three hours is not desirable and is not recommended for future work.

Postshot Site Inspection

30. The donor pad prior to detonation is shown in photograph 21. A revetment wall and the horizontal portion of its fragmentation trap can also be seen along with portions of another revetment and trap. Photograph 22 shows the resulting crater shortly after the donor pad was detonated. The size of the crater was wholly unexpected based on previous experience, being approximately 10 ft deep and 130 ft in diameter. The explosion and crater severely damaged all of the revetment walls and the close-in array of fragmentation traps. Photographs 23, 24, and 25 show the damage to some of the traps that had vertical faces. The lip of the crater appeared to be approximately 10 ft from the original front face of each trap, with that front portion of the trap being completely destroyed. The remaining portion of the trap was too badly broken to be of any value. Photograph 26 is a view of the crater from the A3 trap. Note the lip of the crater on top of the A1 trap.

31. The A2, A3, D2, and D3 traps survived with some cracking (photograph 27) due to the ground shock. These traps were covered with the ejecta from the crater, however, and did not produce any useful penetration data. Photograph 28 shows the ejecta on traps D2 and D3. Trap D3 is shown in close-up in photograph 29. Photograph 30 shows the ejecta on traps A2 and A3. There were no large chunks on these pads as occurred on D2 and D3, but they still had a thin layer of earth on them.

Photograph 31 is a close-up of trap A3, showing a broken corner caused by the air and ground shock. Some fragments initially appeared to be embedded in the traps (photograph 32); however, closer inspection revealed that the fragments were contained only in the ejecta. No fragments were found in any of the traps.

Cylinder Testing

32. Because no fragments were caught in any of the traps, it was not necessary to evaluate all of the control cylinders as it was not essential to know the strength variations throughout each pad. A limited number of cylinders were evaluated, however, to give some indication of the strengths involved.

33. Sixteen of the 131 control cylinders were evaluated for constrained compressive strength on 16 October 1967. The cylinders evaluated were selected so that one cylinder represented the concrete in the vertical portions of A1, B1, C1, D1, E1, and F1, and another cylinder represented the concrete in the horizontal portions of all ten traps. Each cylinder tested had a hardened density that approximated the average density of the concrete in the portion of trap it represented.

34. Each 6-in.-diameter by 12-in.-high cylinder was allowed to remain in its cardboard mold during test. The top and bottom 3 in. of the cylinder were trimmed off, thus producing a 6-in.-diameter by 6-in.-high cylinder. This cylinder was placed in a split-wall confining pipe designed to accommodate the cylinder and its cardboard mold. The closure bolts of

the confining pipe were then torqued to a final closure of 5 ft-lb, and the sample was ready for testing.

35. Load was applied to the 6-in.-diameter surface by means of a 4-in.-diameter loading piston centered on the sample. The piston was forced into the sample at a sample deformation rate of 10 percent deformation per minute. The deformations were recorded by means of a li ar slidewire potentiometer which recorded movements of the testing machine's loading head. Loads were measured by a recording load cell. The output was recorded on an X-Y recorder in the form of a constrained stress (on the loading piston area) versus percent deformation relation. A typical record from this test is shown in Plate 5.

36. A summary of the results of the constrained compression tests for all 16 cylinders is shown in table 3. The values of yield strain, yield stress, and stress at 40 percent deformation were obtained directly from the test records. The average stress to 40 percent deformation is a calculated value which takes into consideration all the oscillations in the stress-deformation record and occurs at a point midway between the yield deformation, ϵ_y, and the 40 percent deformation, $\epsilon_{0.40}$. The average stress, $\bar{\sigma}$, to 40 percent deformation can then be expressed as

$$\bar{\sigma} = \frac{U_p}{(\epsilon_{0.40} - \epsilon_y)} \qquad (9)$$

where U_p is the amount of plastic energy (nonrecoverable) absorbed per unit volume of material. U_p is equal to the area under the constrained stress-deformation curve between ϵ_y and $\epsilon_{0.40}$. An approximate constrained stress-deformation curve for each sample can be constructed by assuming that the elastic portion of the curve is linear from zero to the yield strain and yield stress and that the relation is a straight line from the yield stress to the average stress occurring midway between yield deformation (strain) and 40 percent deformation and a straight line from this point to the stress at 40 percent deformation.

Discussion of Results

Quality control

37. The range and variations of the unhardened densities shown in table 2 are greater than what normally should be expected for cellular concrete used for experimental purposes. These values are real, however, and are primarily a result of the slurry batching equipment which did not have the proper resolution and regulation for the quality control required for this work. Due to time considerations, the equipment on hand at the start of the construction unfortunately could not be substituted in time to benefit the quality control.

38. The unhardened density of the cellular concrete is primarily affected by three things: (a) the density of the slurry, (b) the volume of air added to the slurry in the form of preformed foam, and (c) the mixing techniques involved once the foam has been added. The amount of foam was the same for each batch. The variations in mixing speed, action, and duration from batch to batch were not significant enough to greatly

affect the air content. The amounts of water and cement used to make the slurry did vary considerably, however, due to inadequate resolution in the weigh-batching equipment and malfunctioning of the water-metering system. In a few instances, only a small portion of the required amount of batch water was added to the approximately 4800 lb of cement per batch, thus causing considerable balling of the cement and, ultimately, nonuse of the entire load of cement and water. The amount of cement per batch varied as much as ± 400 lb. If the water content and air content were correct and had remained constant from batch to batch, the variations in cement content that were experienced would only have affected the density of the concrete by approximately 2 pcf. As can be seen from the range of values given in table 2, the density variations were much greater than that. It is interesting to note that of the 132 batches made, 69 were within ± 2 pcf of the design density of 48 pcf. The air content variations in the concrete undoubtedly also contributed to the total density variations in the concrete, but these variations are generally minor based on observations of similar work on other jobs.

Cylinder testing

39. The 16 cylinders were evaluated at concrete ages varying from 12 to 17 days. For the purposes of this report, the effect of age on the strength of the concrete will not be considered because the variations will be small when compared to the variations caused by effects of density and cement and water content variations on strength and will probably be masked by these effects.

40. All of the samples exhibited the desired constrained stress versus deformation characteristics necessary for a fragmentation acceptor material (table 3). The strength of the concrete is affected by the cement, water, and air contents. For any constant water-cement ratio, a strength versus density relation can be established for cellular concrete.[3] It is doubtful that the water-cement ratio was constant for all of the concrete placed and samples made because of the slurry batching equipment difficulties encountered. If it is assumed, however, that the water-cement ratio was constant for the entire operation, strength versus density relations as shown in plates 6 through 8 can be developed. These relations definitely indicate increasing strengths with density increases and, by means of the statistical tolerance limits, show the data dispersion probably caused for the most part by variations in the water and cement contents. The strengths indicated by the test cylinders were probably lower than the strength in the traps on D-day because of the pseudo-autoclave curing the trap concrete received and the early age at which the concrete was to be tested. Generally, high temperatures and steam curing tend to produce high early strengths which do not improve much with increasing age.

41. The relation between the unit weight of the unhardened density (unit weight) and the hardened density of each sample at testing is shown in plate 9. This relation is affected by many factors which include plastic shrinkage, moisture changes, and errors in weighing and measuring. The line of best fit is shown in plate 9 for the readers' general information.

PART V: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

42. Results of this limited investigation of the use of cellular concrete as a material for fragmentation acceptors indicate that:

<u>a</u>. A correlation between depth of fragment penetration and impact velocity for a fragment of a given size, shape, and orientation impacting on a cellular concrete of a given design can be made.

<u>b</u>. Cellular concrete as demonstrated in the laboratory has the desired physical characteristics necessary for a suitable acceptor material and can be impacted and penetrated by a moving projectile with little or no resulting rebound, cracking, or splitting.

<u>c</u>. Cellular concrete can be easily fabricated for and placed in field acceptor blocks. The field control achieved for this job was not ideal due to the inadequacies and malfunctioning of the slurry-batching equipment, but experience in both the laboratory and on other field jobs has indicated that the proper control can be achieved with the proper equipment.

<u>d</u>. The thermal cracking observed in a few sections appeared to be related to the air temperature and wind velocity during the time the sections were placed and cured. Sections placed early in the morning on hot, still days exhibited thermal cracking, while sections placed late in the afternoon or on very windy days did not.

Recommendations

43. As cellular concrete appears to be satisfactory for use as a fragmentation acceptor material, its use in future work of this type is recommended. Additional laboratory work is necessary to optimize the strength and void characteristics of the cellular concrete with respect to the most ideal properties for fragment penetration. The effects on total penetration of various shaped and size fragments and their orientation at impact are also recommended for future study.

44. The effects of meteorological conditions on the thermal cracking of large monolithic sections of cellular concrete placed continuously should be studied to determine under what conditions this cracking will occur and the limitations of placing with respect to rate, size of lift, and time.

LITERATURE CITED

1. Hoff, G. C.; Shock-Absorbing Materials; Backpacking Materials for Deeply Buried Protective Structures; Technical Report No. 6-763, Report 1, March 1967, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.; Unclassified.

2. Hoff, G. C.; Shock-Absorbing Materials; Selection of a Suitable Low-Density Concrete for Backpacking for a Proposed Field Test; Technical Report No. 6-763, Report 3, November 1967, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.; Unclassified.

3. Hoff, G. C.; Shock-Absorbing Materials; Cellular Concrete as a Backpacking Material; Technical Report No. 6-763, Report 2, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss. (in preparation); Unclassified.

4. Hoff, G. C.; Operation FLINTLOCK, Project PILE DRIVER, Project Officer's Report, Report 1, Cellular-Concrete Backpacking Fabrication, Placement, and Control; U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss. (draft); For Official Use Only.

5. Sullivan, B. R. and A. A. Bombich; Blast Attenuation Studies in Dividing Wall Protective Construction; Miscellaneous Paper No. 6-840, September 1966, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.; Unclassified.

6. Sullivan, B. R. and A. A. Bombich; Evaluation of Methods of Attenuating Blast Pressures on Walls; Miscellaneous Paper No. 6-856, November 1966, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.; Unclassified.

Table 1

Summary of Laboratory Impact Test Results

Shot No.	1	2	3
Projectile weight, lb	2.3	2.3	2.3
Projectile length, in.	7.5	7.5	7.5
Impact area, sq in.	3.1	3.1	3.1
Impact velocity, fps	200	310	380
Kinetic energy, ft-lb	1400	3400	5150
Depth of penetration, in.	5.5	8.75	11.75

Table 2

Summary of Quality Control Unit-Weight Test Results

Trap Designation	Approximate Volume of Concrete cu yd	No. of Trucks	No. of Samples	Total Placing Time hr:min	Mean Value of Unit Weight pcf	Range of Unit Weight Values pcf	Standard Deviation of a Single Observation + pcf
A1	78	14	14	3:30	47.4	44.5 - 52.2	4.27
A2	67	12	12	2:40	47.5	44.5 - 51.0	1.59
A3	67	12	11	3:30	46.7	43.0 - 56.0	3.56
B1	78	14	14	3:10	45.8	41.1 - 49.6	2.14
C1	78	14	14	5:00	48.4	44.5 - 54.5	3.00
D1	78	14	14	3:40	45.3	40.5 - 48.0	1.83
D2	67	11	11	3:55	48.5	44.8 - 55.4	3.37
D3	67	12	12	2:55	50.2	44.2 - 57.5	3.77
E1	78	15	15	3:35	47.6	44.0 - 52.2	1.76
F1	78	14	14	4:40	46.6	40.2 - 52.2	3.44
Totals	736	132	131	36:35	47.4*	40.2 - 57.5*	2.95*

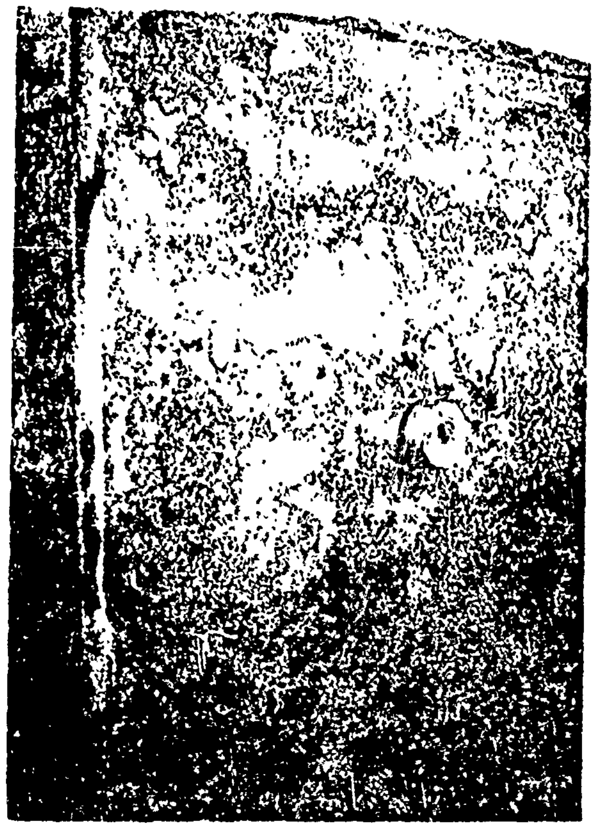
* These values represent the 131 samples combined as one population.

Table 3

Summary of D-Day Cylinder Strength Data

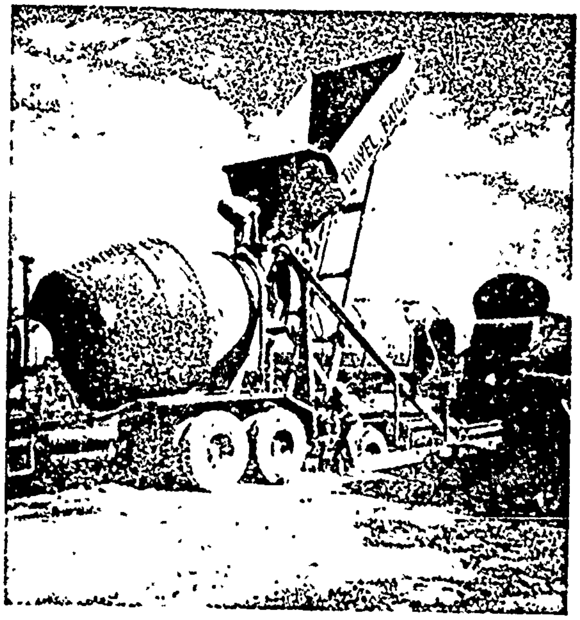
Trap Designation	Sample No.	Age days	Hardened Density pcf	Yield Strain in./in.	Yield Stress psi	Average Stress to 40% Deformation psi	Stress at 40% Deformation psi
A1(FF)*	2	14	44.4	0.035	495	667	905
A1	8	13	48.8	0.030	545	712	990
A2	5	12	48.8	0.020	655	888	1230
A3	9	12	49.3	0.030	605	849	1230
B1(FF)*	1	14	43.8	0.019	460	590	800
B1	13	14	44.5	0.030	440	562	745
C1(FF)*	3	14	46.6	0.036	455	555	680
C1	9	14	44.4	0.030	395	498	615
D1(FF)*	1	14	45.6	0.033	415	574	810
D1	12	13	44.2	0.040	340	431	590
D2	10	17	47.0	0.028	570	732	995
D3	11	17	50.5	0.015	670	882	1280
E1(FF)*	1	12	47.4	0.030	570	721	955
E1	11	12	49.8	0.038	530	644	815
F1(FF)*	1	16	44.4	0.023	405	532	650
F1	7	16	46.8	0.023	470	603	825

* Denotes sample representing concrete in vertical portion of fragmentation trap.

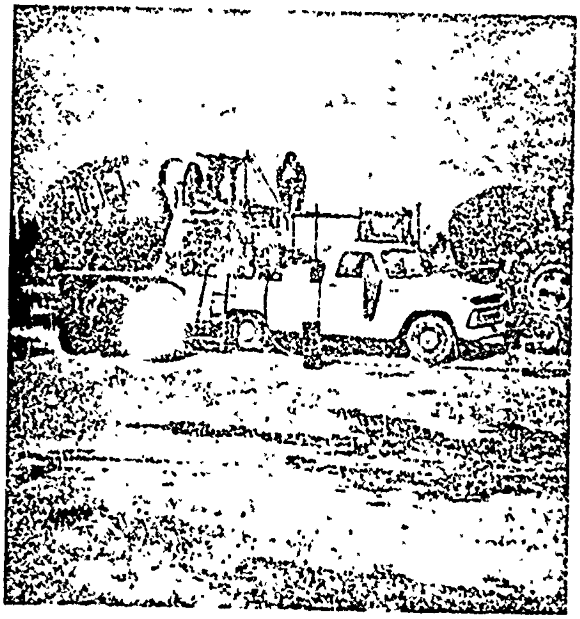


Photograph 1. Round No. 1

Photograph 2. Round No. 2

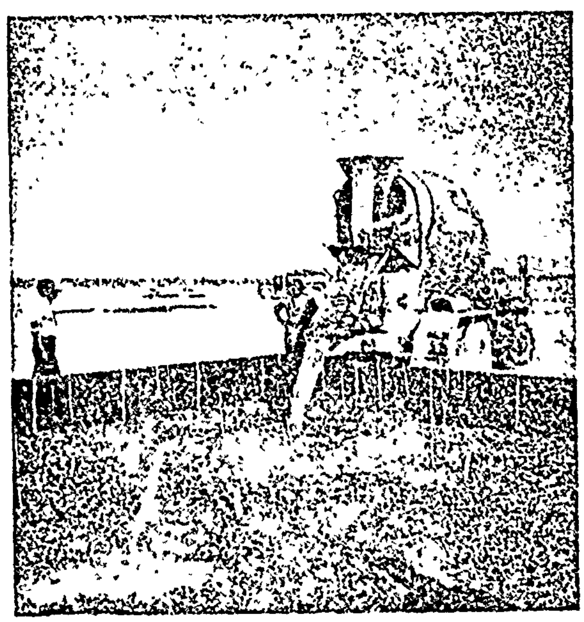


Photograph 3. Slurry batching operation

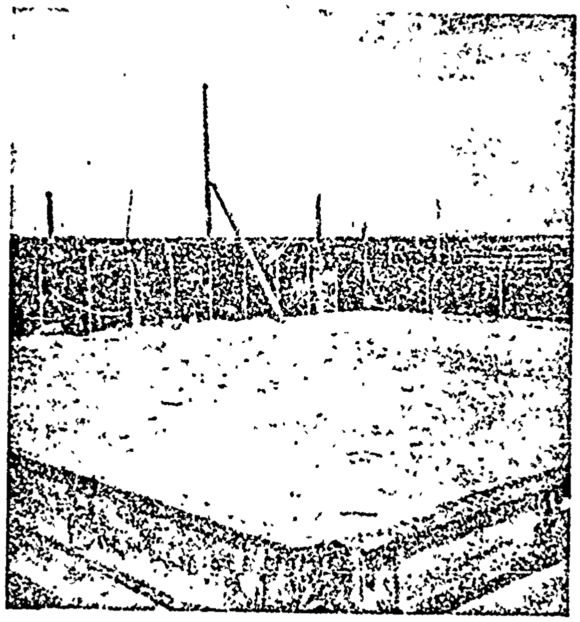


Photograph 4. Foam generating operation

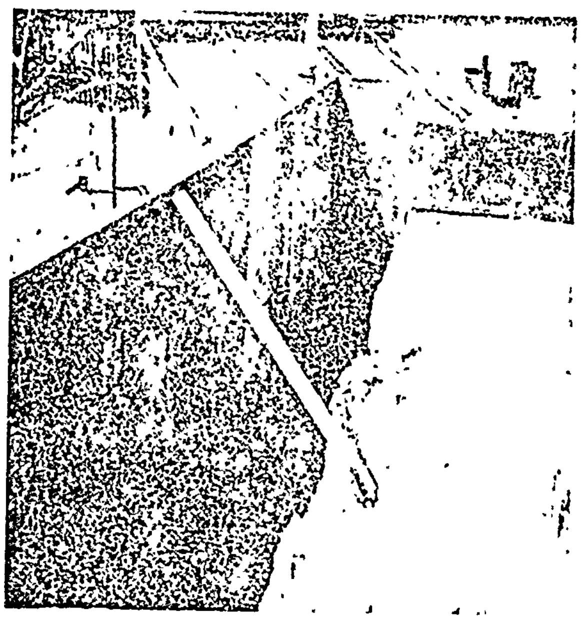
Photograph 5. Foam discharging into mixer truck



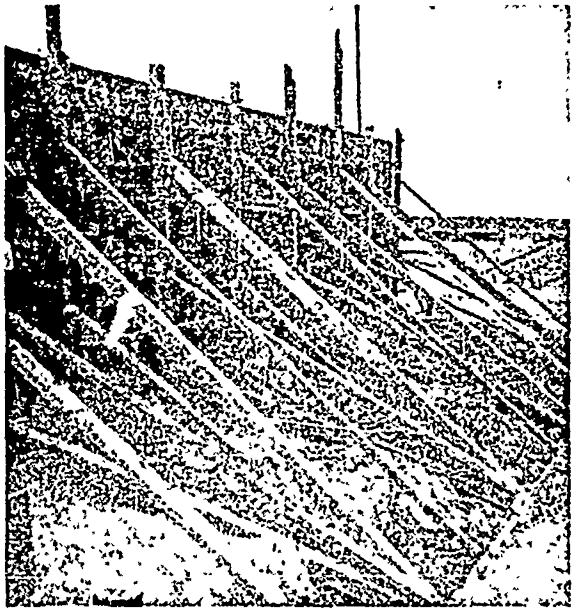
Photograph 6. Cellular concrete placing operation



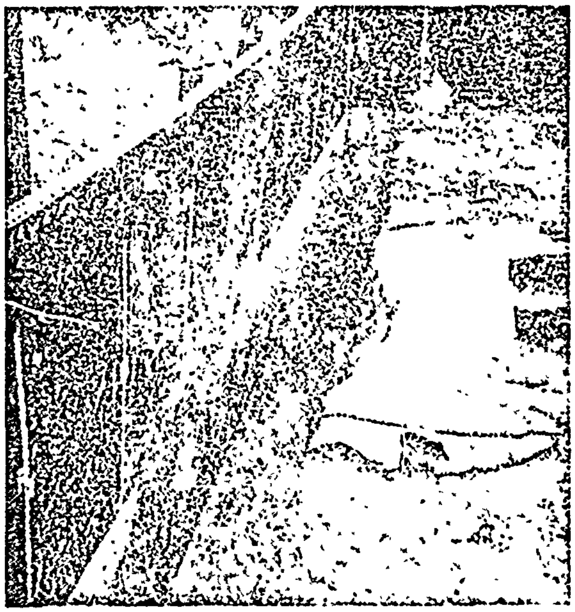
Photograph 7. Rear view of trap E1 formwork



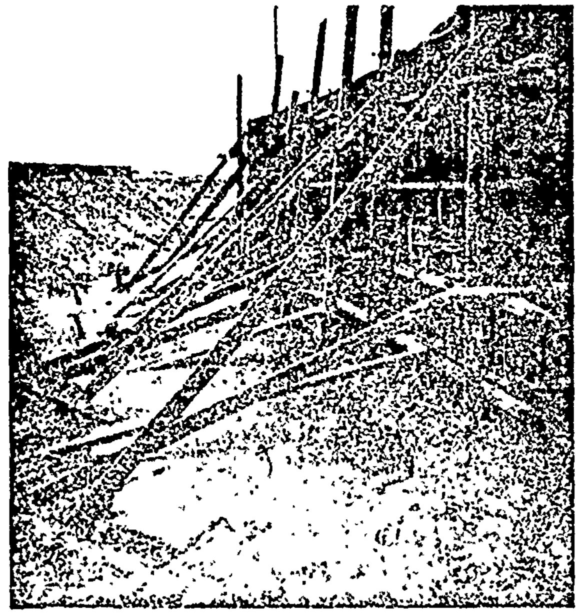
Photograph 8. View of trap E1 vertical face formwork



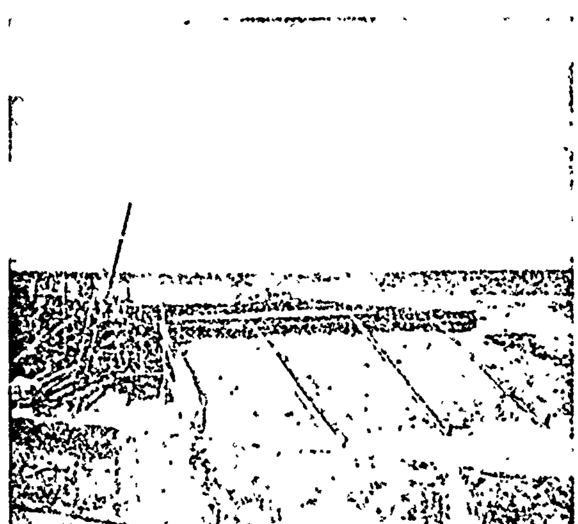
Photograph 9. Bracing of vertical face formwork of trap A1



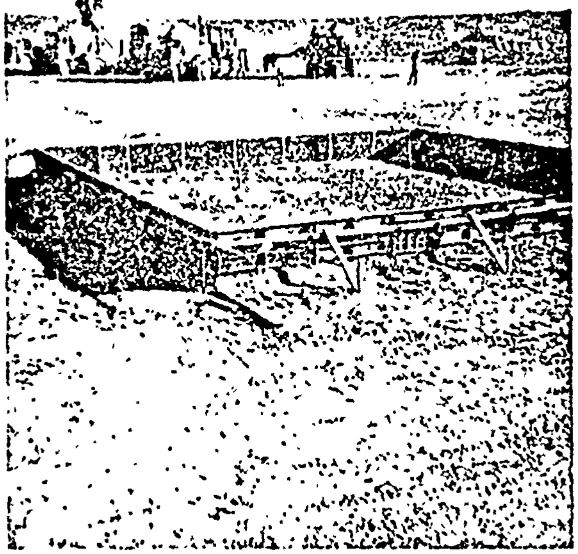
Photograph 10. Buckled formwork of trap A1



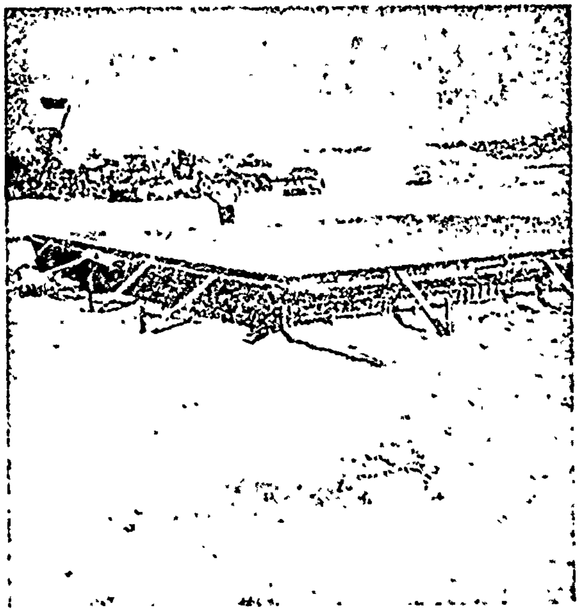
Photograph 11. Failed formwork of trap A1



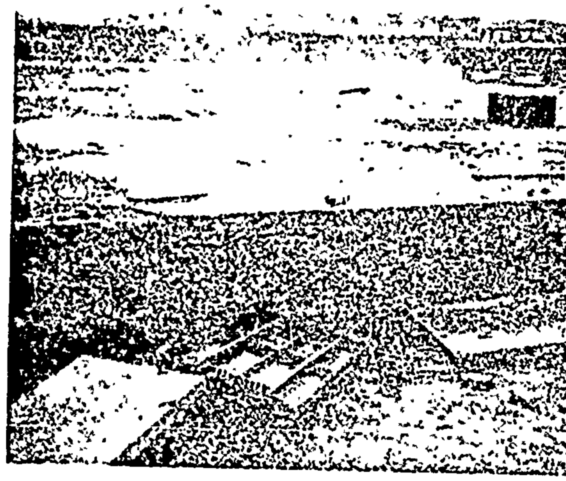
Photograph 12. View of trap F1 formwork



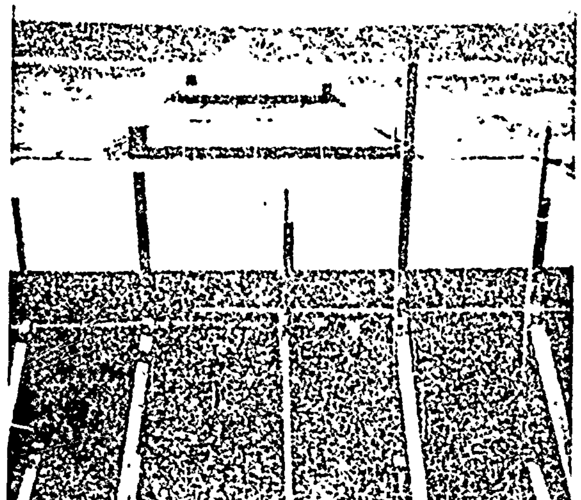
Photograph 13. View of trap D3 formwork



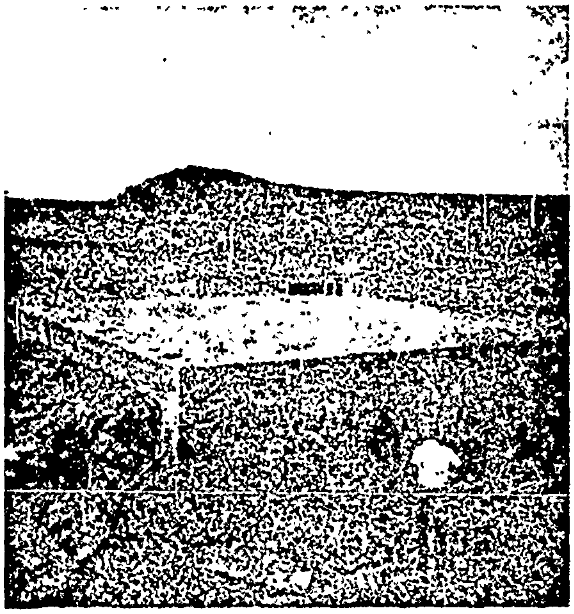
Photograph 14. Completed trap D3



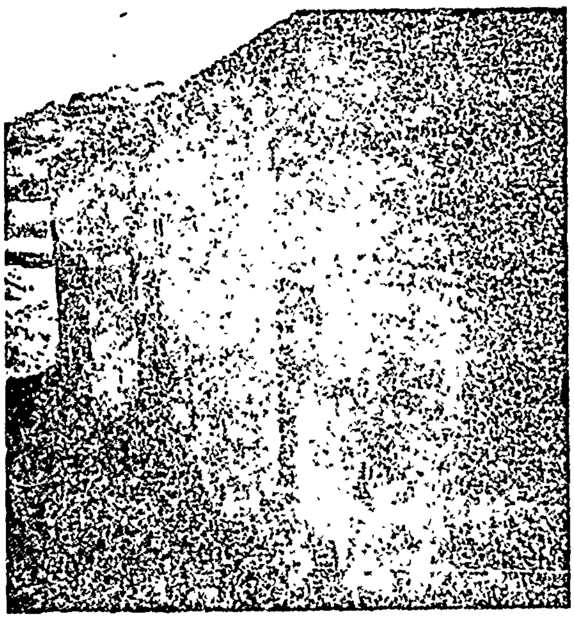
Photograph 15. Completed trap A3



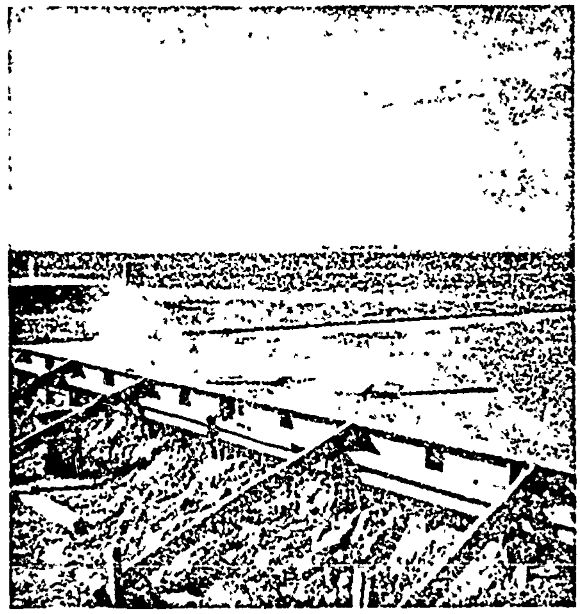
Photograph 16. Traps A1, A2, and A3



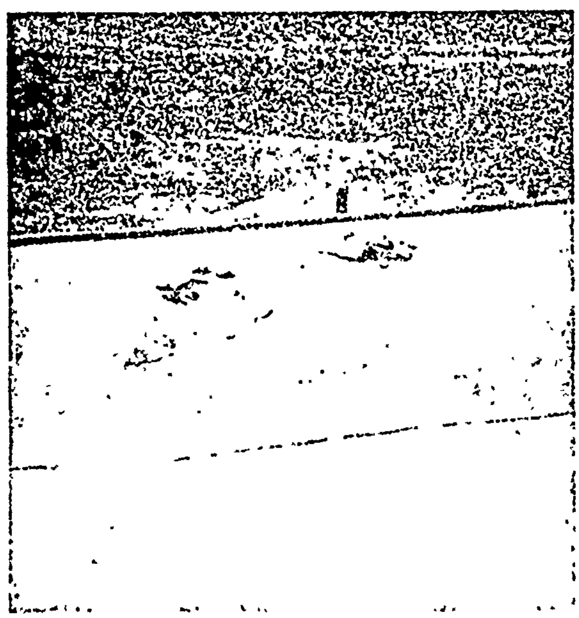
Photograph 17. Completed trap F1



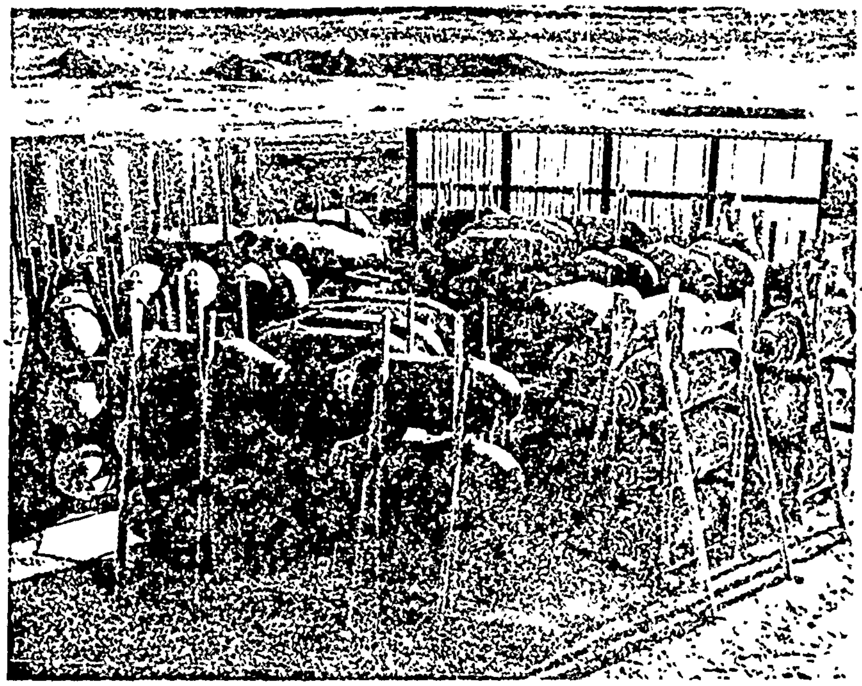
Photograph 18. Front face of trap F1



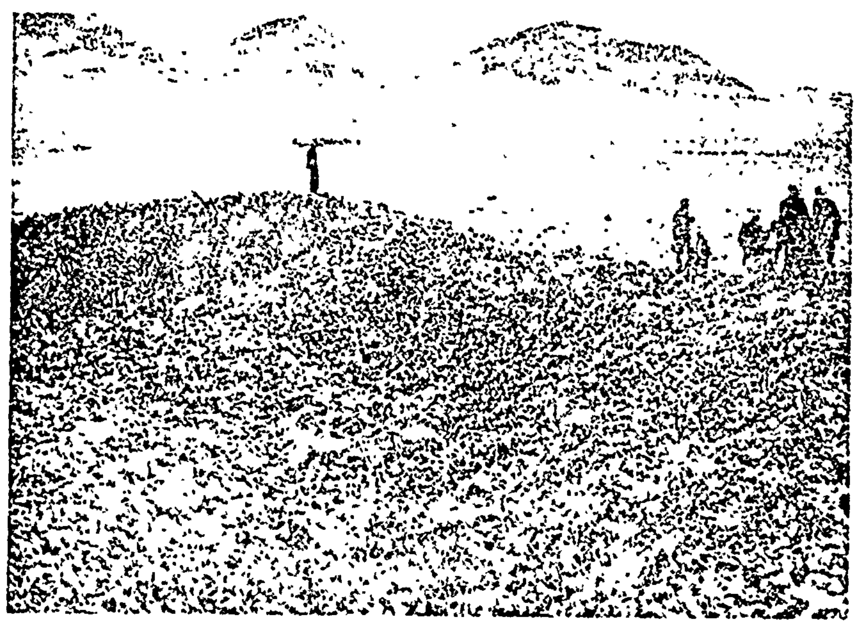
Photograph 19. Thermal cracking in trap D3



Photograph 20. Thermal cracking in trap D3

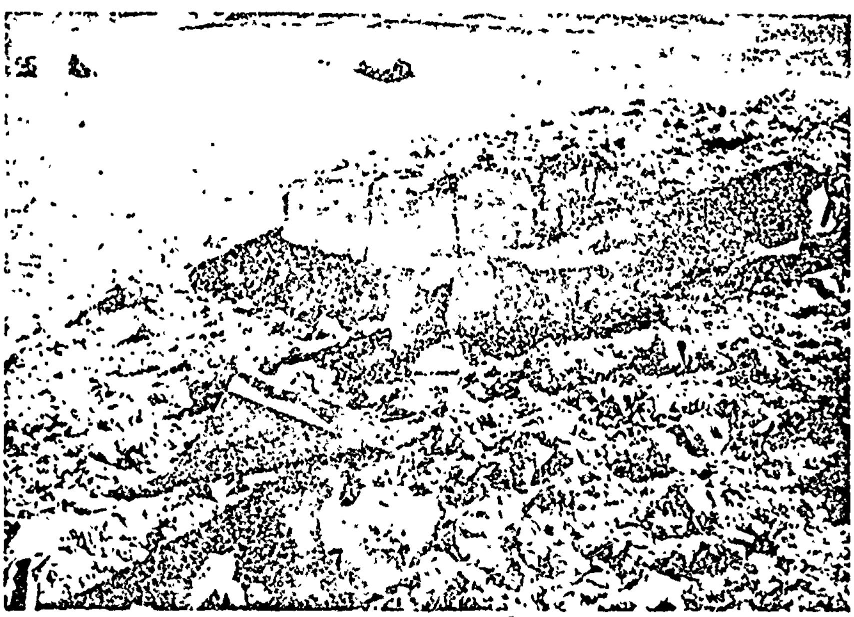


Photograph 21. Munitions stack

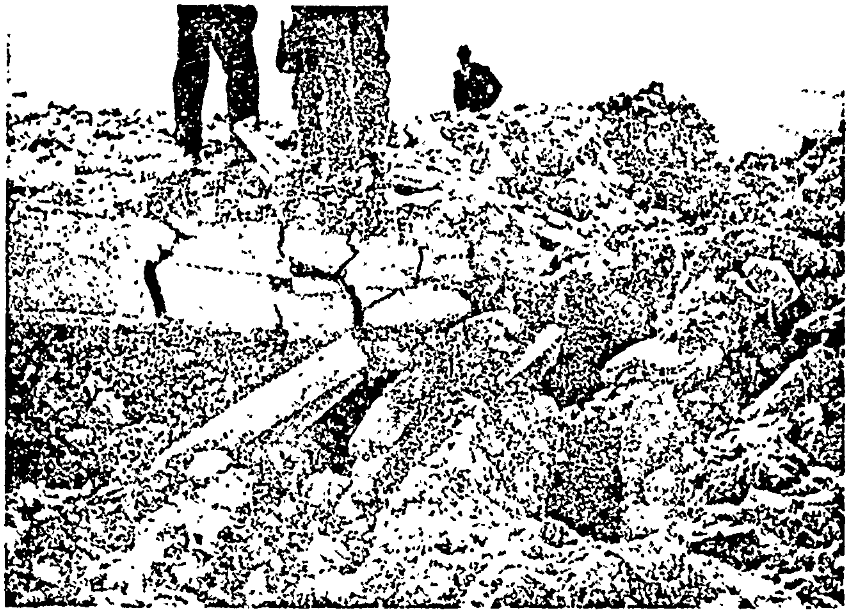


Photograph 22. Postshot crater

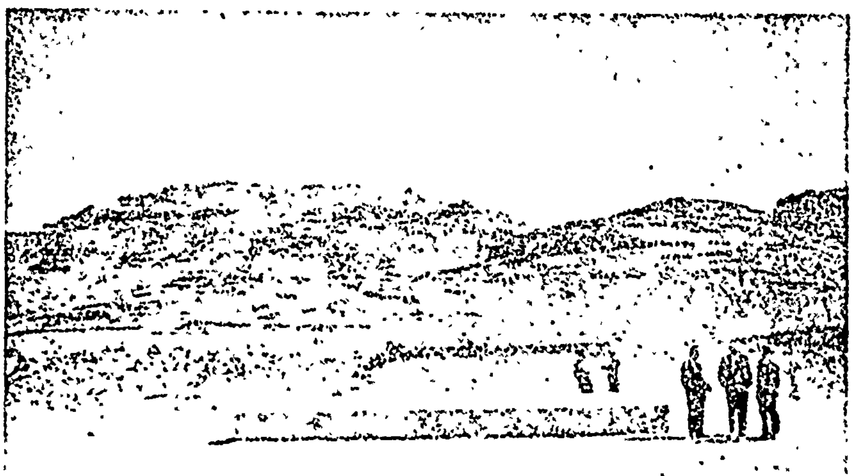
Photograph 23. Postshot view of trap B1



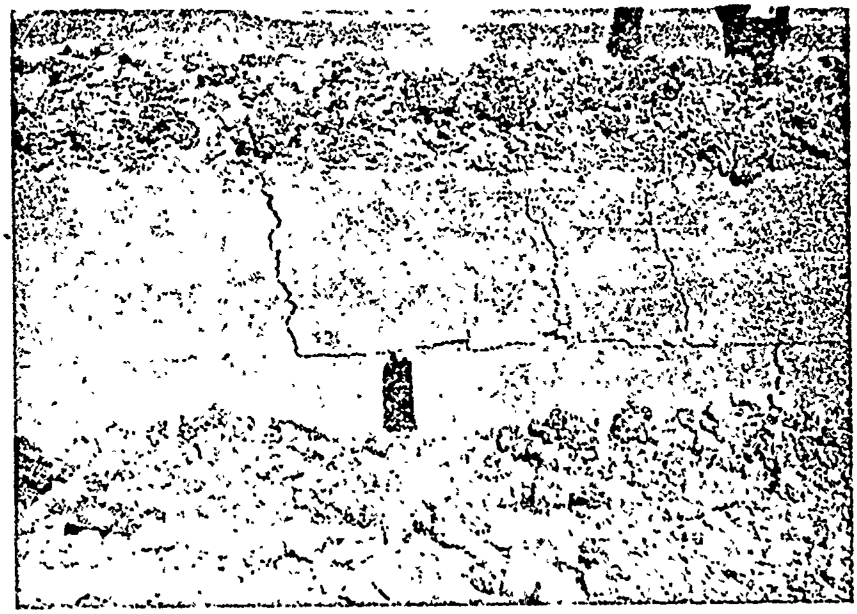
Photograph 24. Postshot view of trap E1



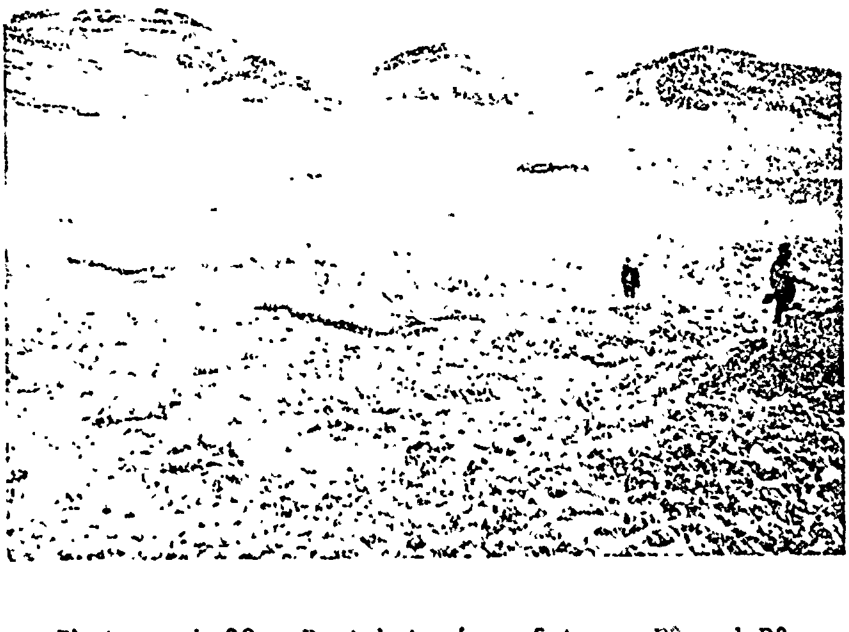
Photograph 25. Postshot view of trap D1



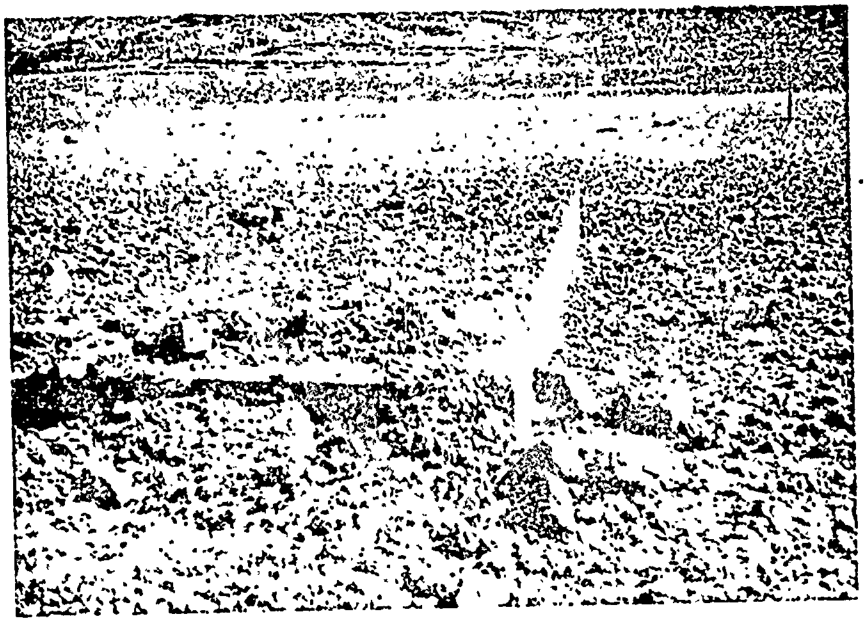
Photograph 26. Postshot view of traps A1, A2, and A3



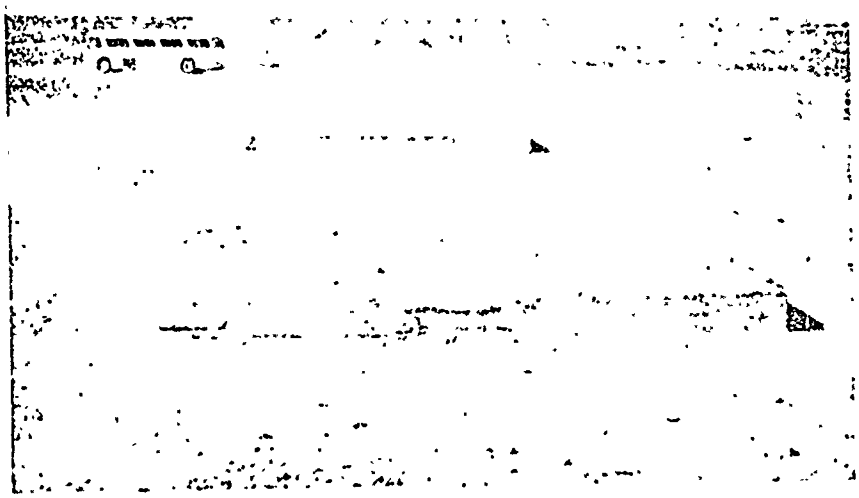
Photograph 27. Postshot side view of trap D1



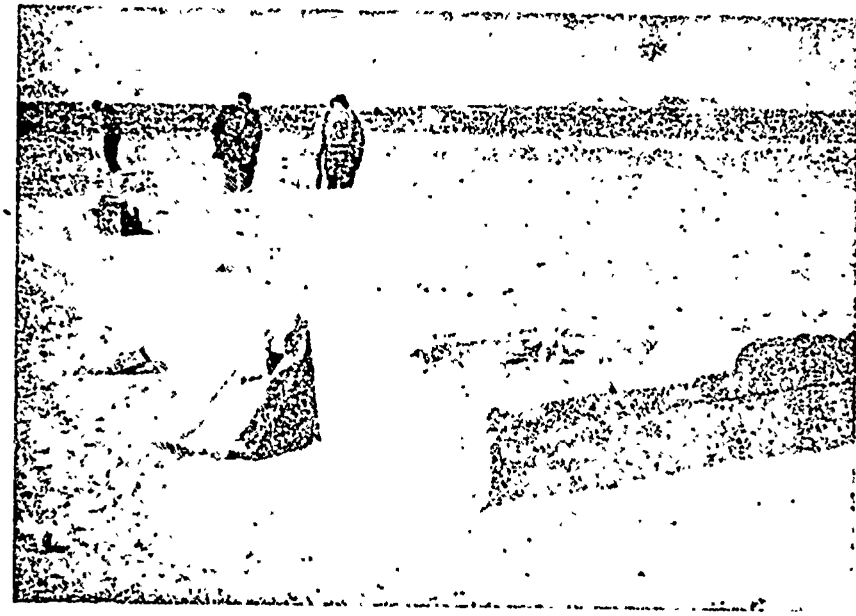
Photograph 28. Postshot view of traps D2 and D3, showing ejecta covering



Photograph 29. Postshot view of trap D3, showing ejecta covering

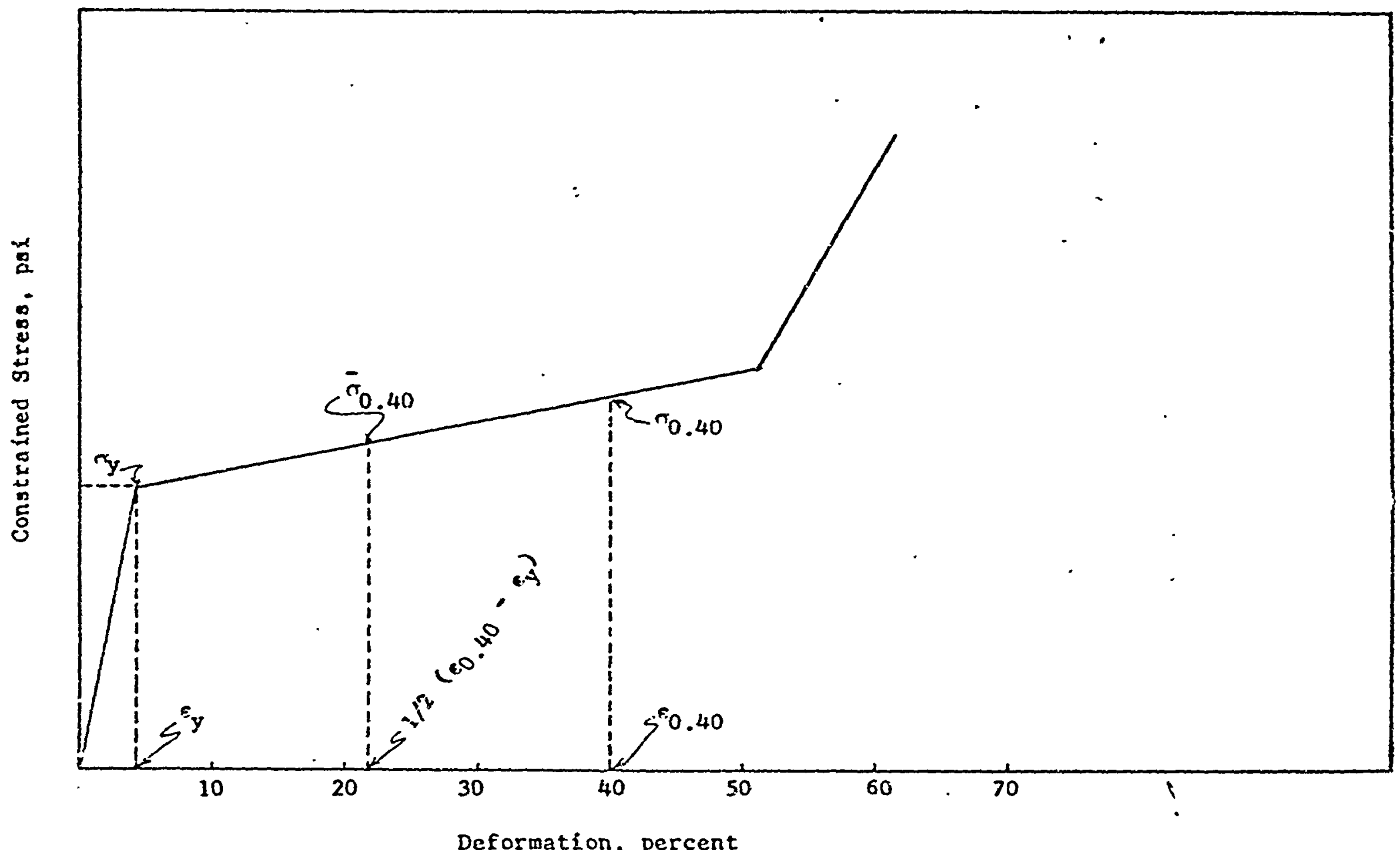


Photograph 30. Postshot view of traps A2 and A3, showing ejecta covering



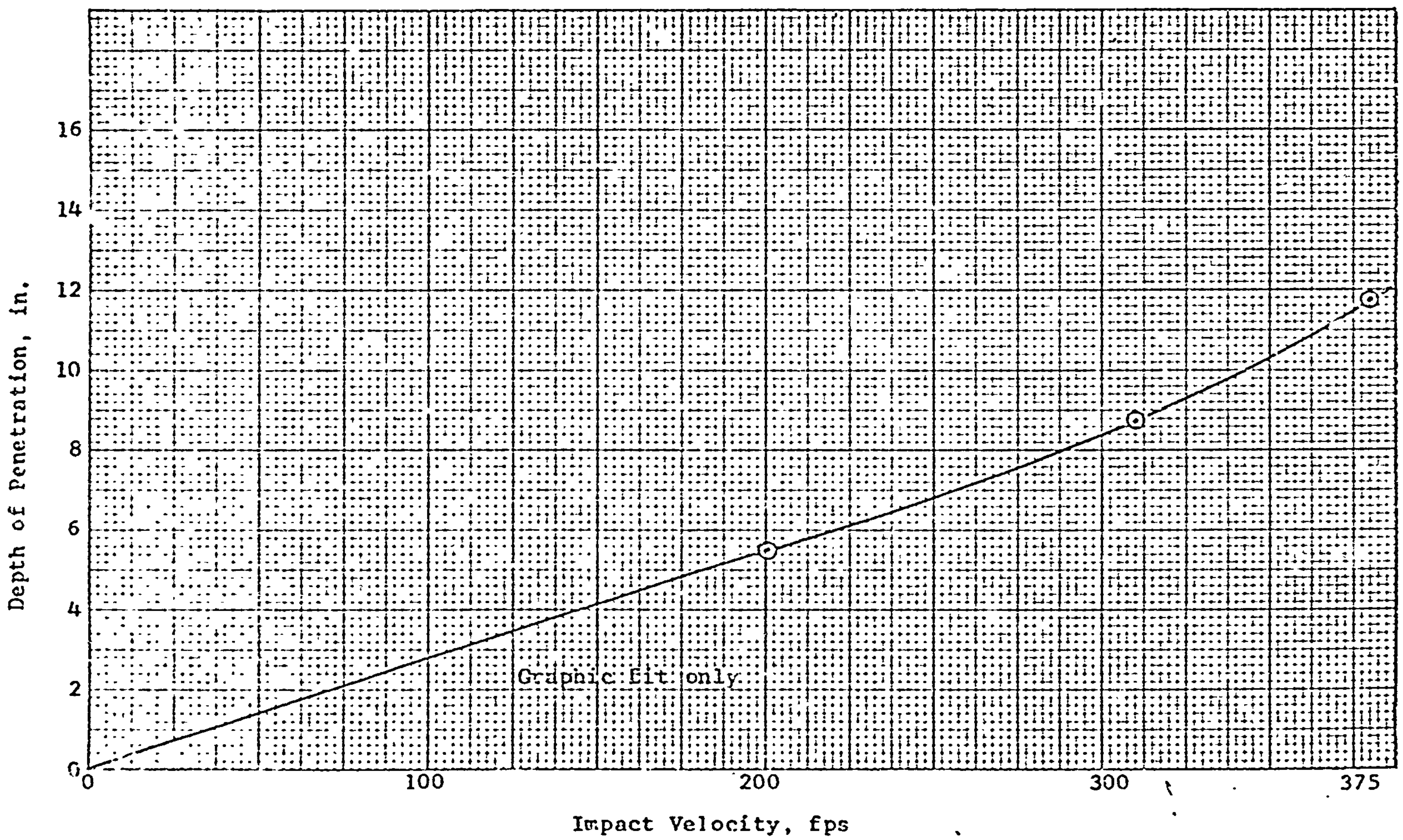
Photograph 31. Postshot view of trap A3, showing ejecta covering

Photograph 32. Postshot view of fragment in ejecta covering of trap D2



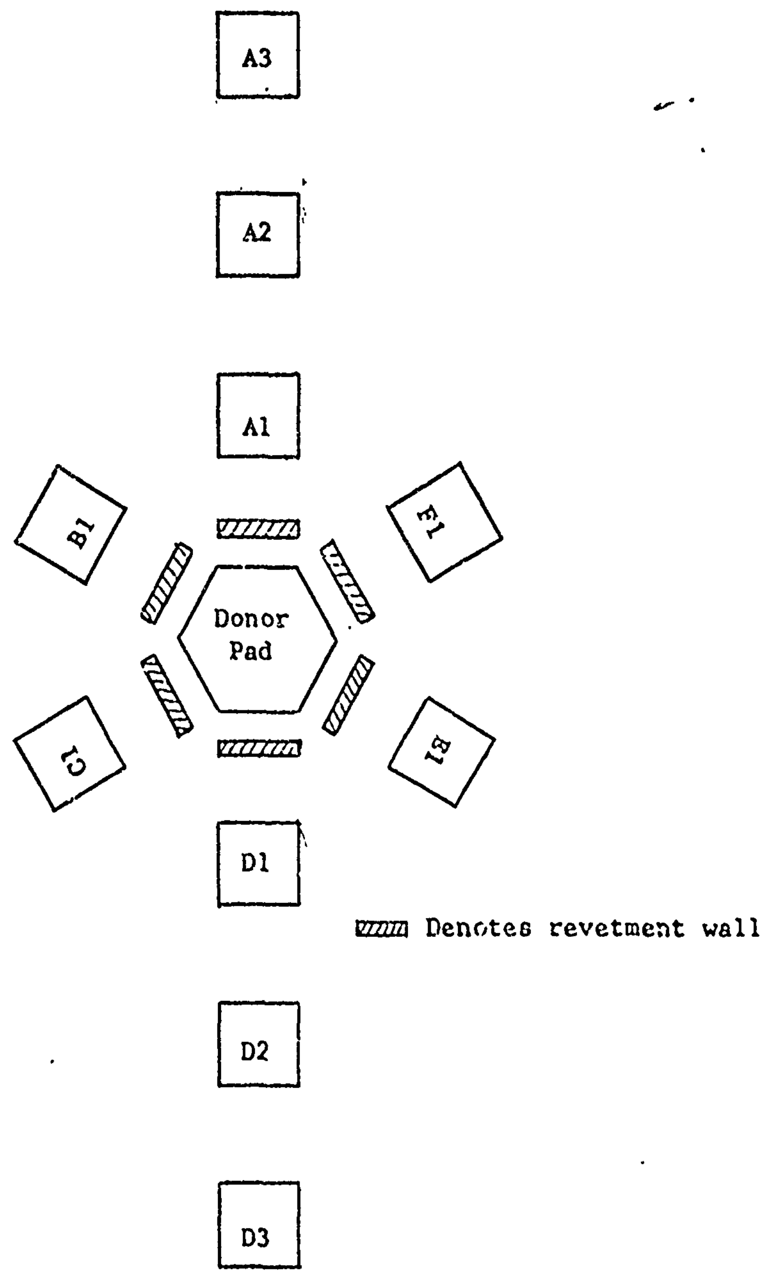
Typical Constrained Stress
Versus Deformation Relation
for Cellular Concrete

PLATE 1



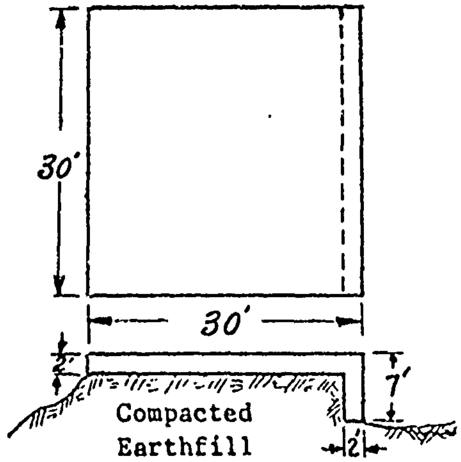
Depth of Penetration Versus
Impact Velocity Relation

PLATE 2

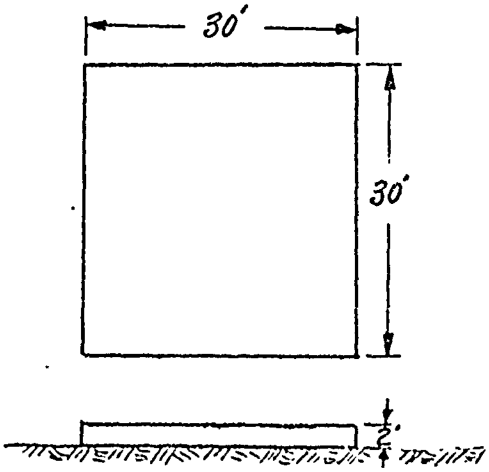


Fragmentation Trap Locations

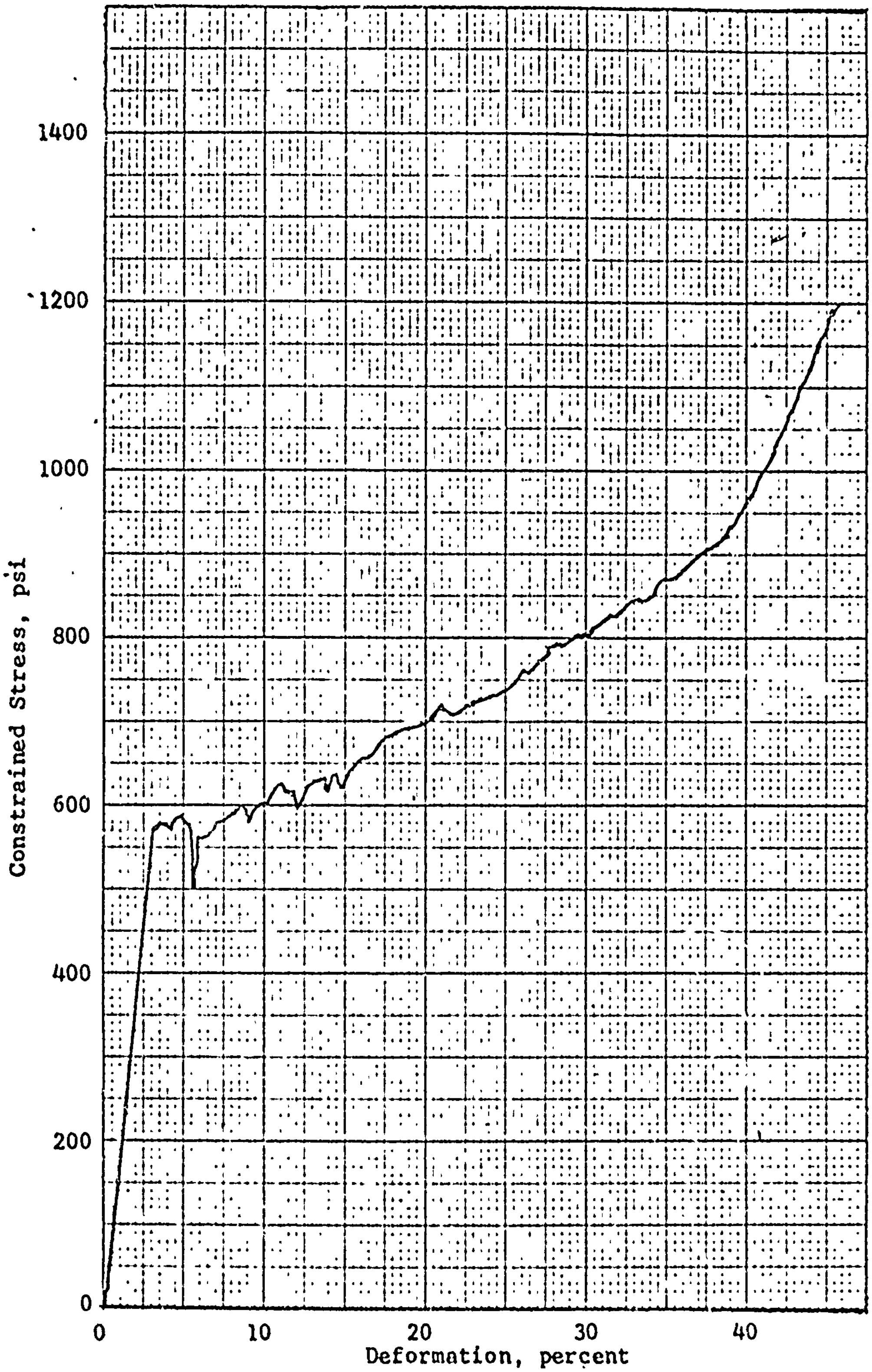
PLATE 3



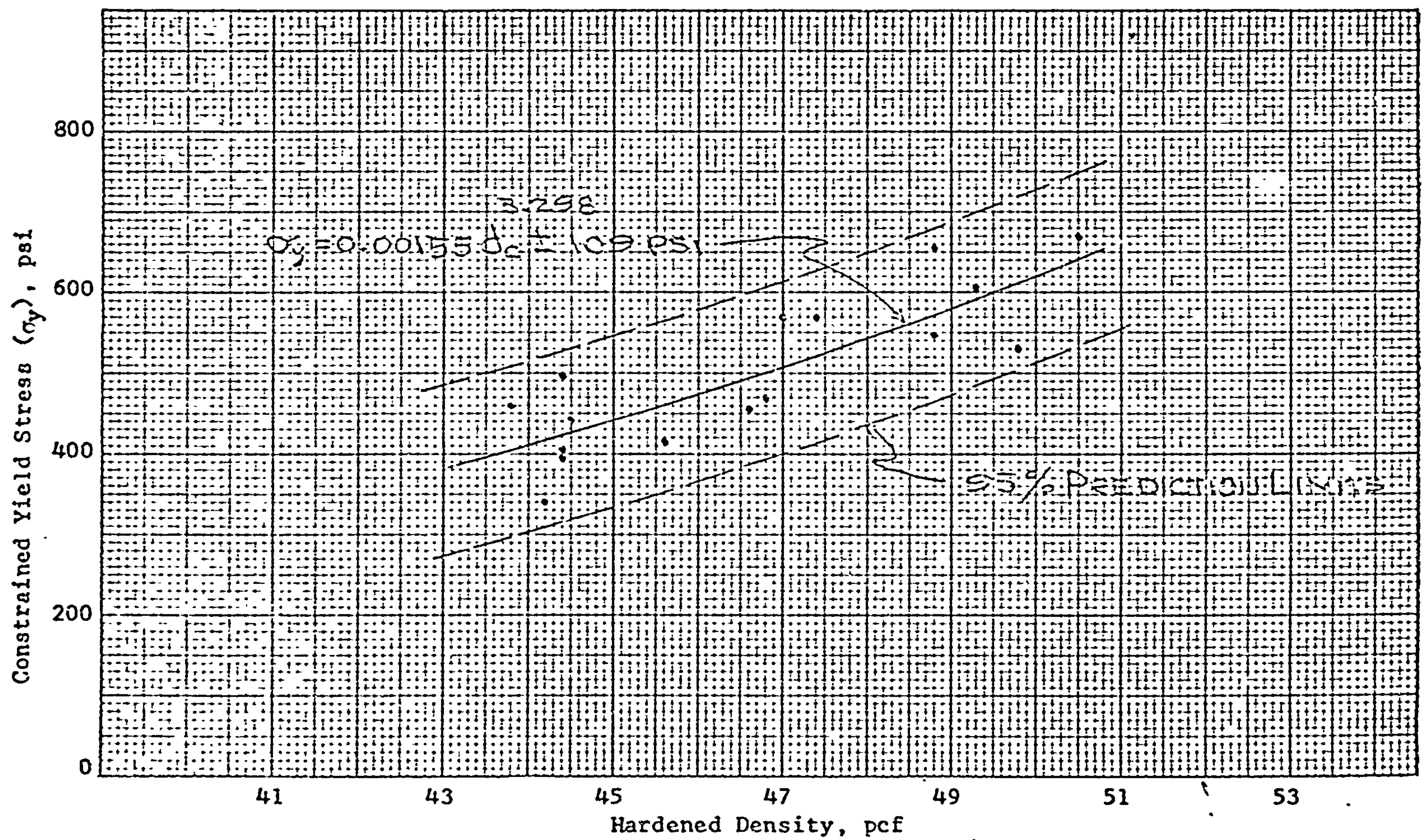
a. Trap with vertical face



b. Trap without vertical face

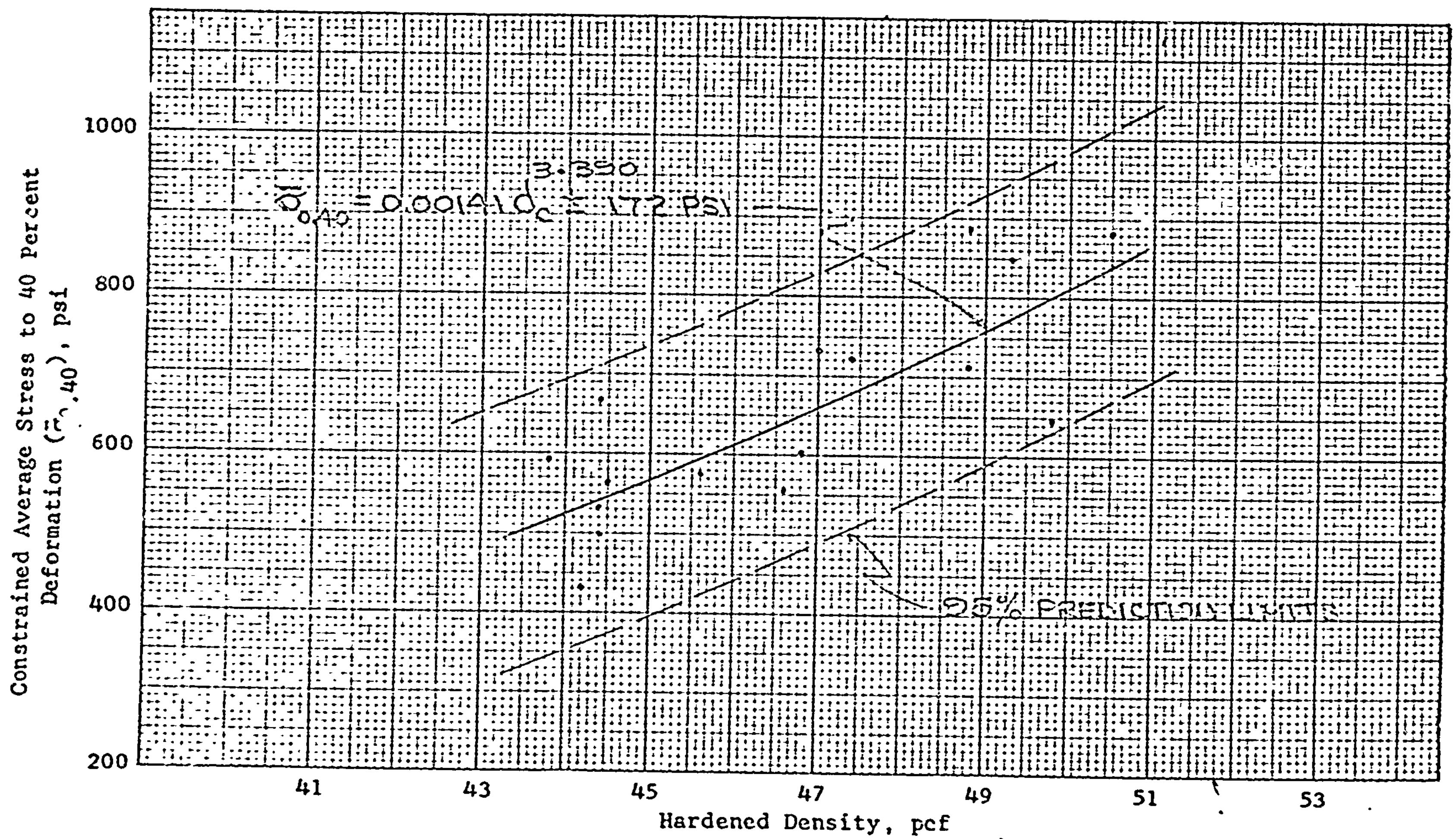


Typical Constrained Stress-Deformation Curve for Cellular Concrete (Sample E1-1)



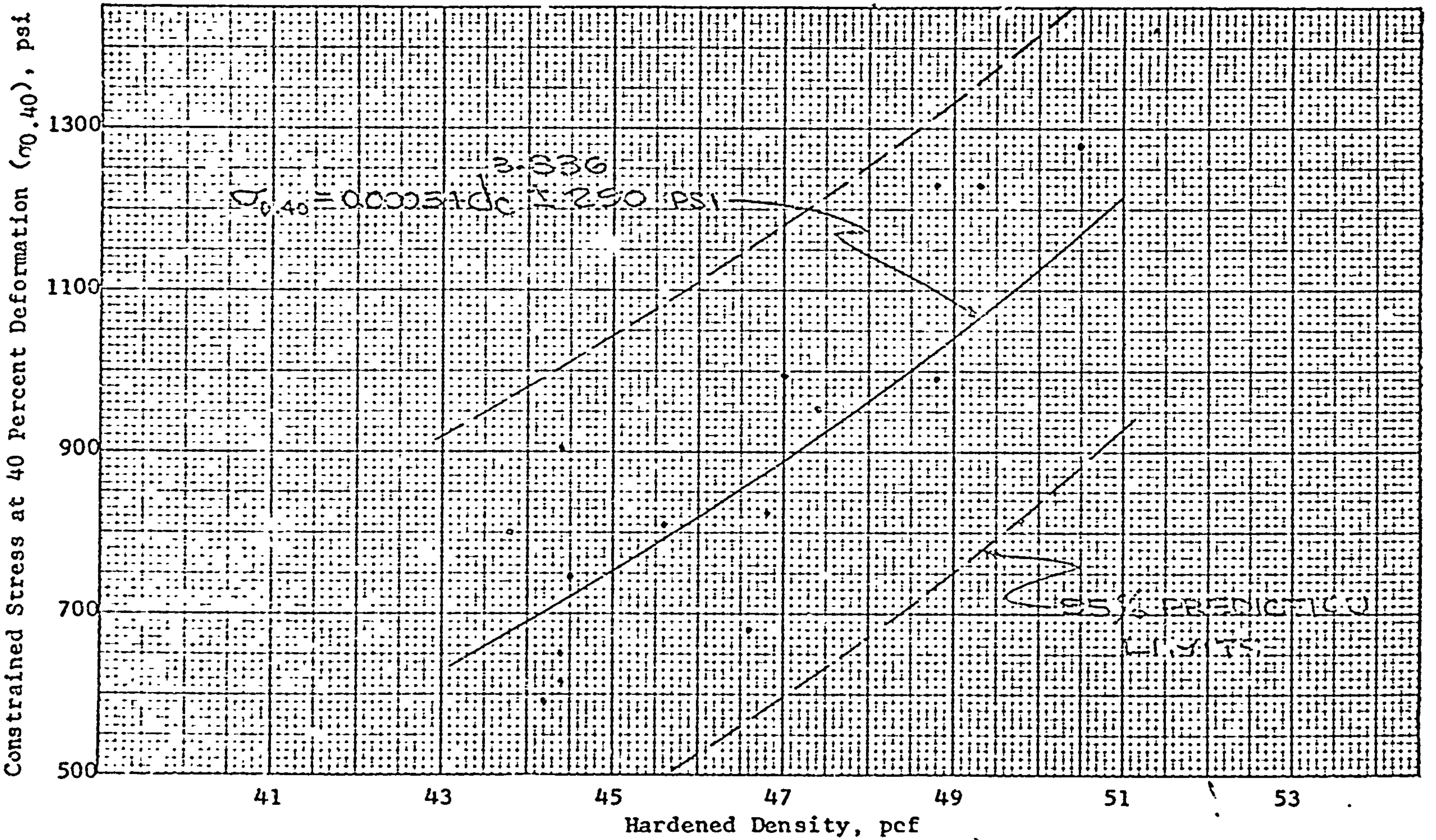
Constrained Yield Stress Versus Hardened Density Relation

PLATE 6



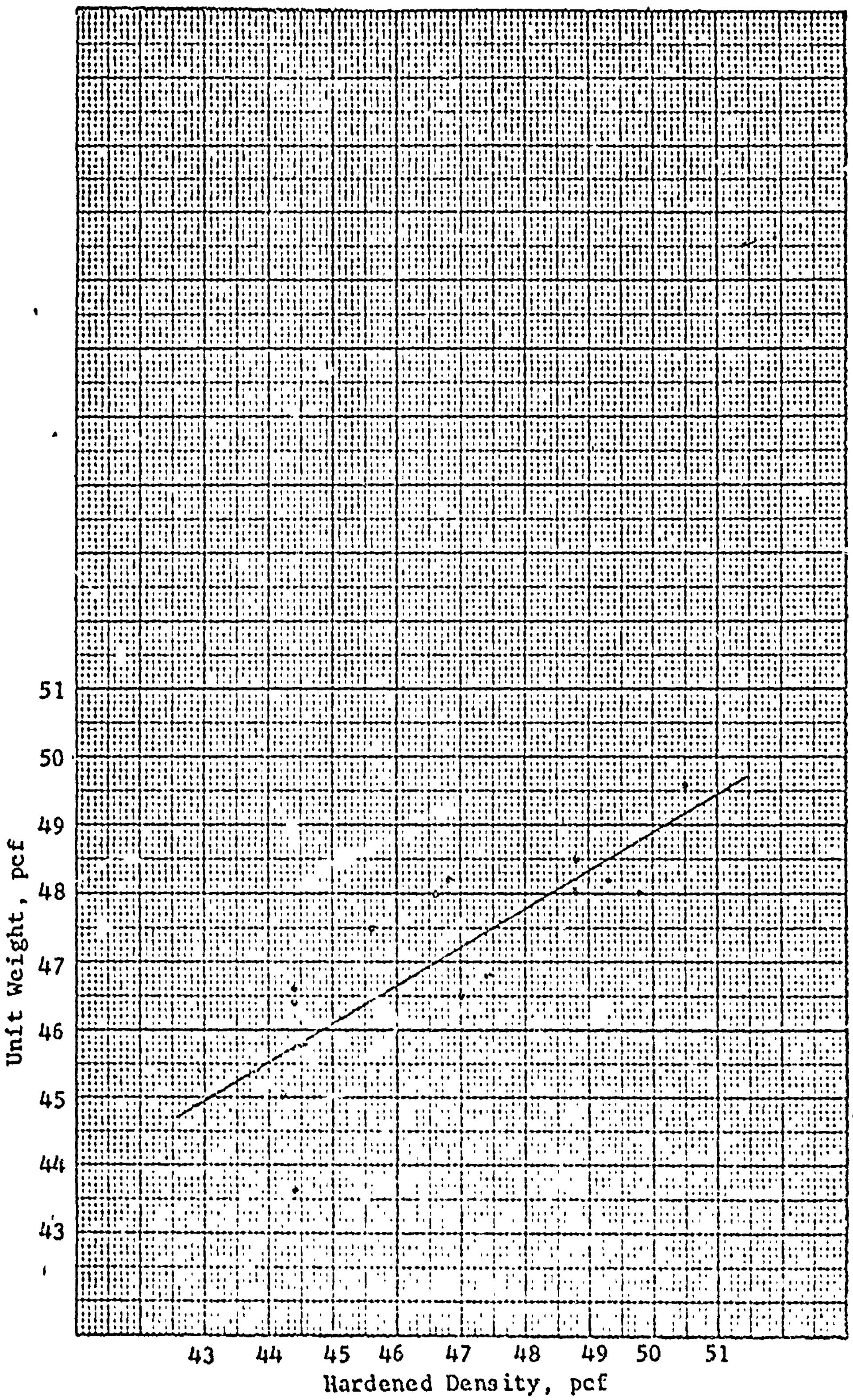
Constrained Average Stress
Versus Hardened Density
Relation

PLATE 7



Constrained Stress at 40 Percent Deformation Versus Hardened Density Relation

52



Unhardened Density (Unit Weight) Versus Hardened Density Relation

PLATE 9

4.2 Composition and Quality: The foamed concrete shall be composed of portland cement, water and a preformed foam. The foamed concrete shall be produced by thoroughly mixing the water and cement into a slurry and then adding preformed foam and mixing for the specified time. Mixtures will be designed to meet the requirements of the fragmentation traps. Changes in the mix design will be made during construction operations as determined necessary.

5. MATERIALS:

5.1 Cement: Portland cement shall conform to ASTM Standard C 150-63, type III, including the requirement for control of false set contained therein. The average value of the fineness (specific surface, square centimeters per gram) of the type III portland cement, as determined by the air permeability test (ASTM Standard C 204-55) of the first lot received shall be not less than 4600 square centimeters per gram with a minimum value of any one sample not less than 4400 square centimeters per gram. All additional lots received shall have an average minimum fineness, as determined in the same manner as the first lot, with ± 200 square centimeters per gram of the fineness value of the first lot with the minimum value of one sample being 200 square centimeters per gram less than the average minimum value of the lot being evaluated.

5.2 Source: The contractor shall provide the Contracting Officer with the name of the mill from which cement will be obtained at least seven days in advance of the time when placing of foamed concrete is expected to begin.

5.3 Foaming Agent: The foaming agent to be used in producing preformed foam shall be one of the following four available foaming agents, or approved equal: Chemical Concentrate Foaming Agent, Mearlcrete, Elastizell or Nationalcrete. Foaming agent to be used on the job shall be from the same batch and lot. The foaming agent shall be protected during storage in accordance with the recommendations of the manufacturer.

5.4 Water: The water used shall be clean and free from deleterious amounts of acids, alkalies, or organic materials. No ice shall be permitted to enter the mixer. Extremes of temperature in the mixing water shall be prevented and the temperature shall be maintained reasonably uniform during each day's operations, all within limits as directed.

6. FORMS:

6.1 General: Forms shall be true to line and grade and sufficiently rigid to prevent objectionable deformation under load. The forms shall be sufficiently tight so as to prevent leakage of the fluid foamed concrete. Particular care shall be taken to fit the forms to ground surfaces and to

Water-cement ratio (by weight) = 0.65
Unhardened unit weight = 48 pcf
786 lb or 8.36 bags (94 lb per bag)
Type III cement per cubic yard
511 lb or 61.3 gallons water (73 F) per cubic yard
Foaming agent concentrate as necessary to achieve the air content necessary to obtain the above-mentioned density but will be approximately 0.2 gallons per cubic yard.

Ten calendar days prior to the commencement of the foamed concrete placement operations, the Contracting Officer will evaluate the performance of the contractor's foaming, mixing, and placing equipment and, if necessary, adjust the above mixture proportions to correspond to differences in equipment performance. During production, changes will be made in the mix proportions when and as determined necessary by the Contracting Officer in order to produce the desired strength and uniformity.

8. FIELD TEST SPECIMENS AND CONTROL:

Samples of foamed concrete will be taken by the Government during the progress of the work for the determination of unit weight and for molding test specimens. The contractor shall provide adequate space for the personnel engaged in sampling, testing, and fabricating specimens and shall provide storage space for the test specimens, near the fragmentation traps and of adequate size to accommodate all specimens fabricated and with suitable isolation from construction operations.

9. BATCHING AND MIXING:

9.1 General: The contractor shall provide batching and mixing equipment having a capacity suitable for the job. Batching and mixing may be totally accomplished at a location near the fragmentation traps or may be accomplished in a two-stage operation, which a cement and water slurry batched and mixed off-site and preformed foam added and final mixing accomplished at the test site. The two-stage batching and mixing operation will be permitted only if the conveying of the slurry meets approval of the Contracting Officer. If specifically approved, cement-water slurry mixed off-site may be of a drier consistency than required in the final mixture and the necessary additional water added during final mixing operations. All batching and mixing operations shall be strictly as approved by the Contracting Officer and shall be modified when directed in order to obtain the desired results. All batching and mixing shall be done in the presence of, and will be directed by, the Contracting Officer.

9.2 Batching equipment:

9.2.1 Cement: If bulk cement is used, approved batching equipment shall be provided. Batching shall be by weight and the equipment may be manual or semi-automatic. Weighing equipment shall include a visible springless dial, which shall indicate the scale load at all stages of the weighing operation, or shall include a beam scale with a beam balance indicator which shall show the scale in balance at zero load and at any beam setting. If preliminary mixing of cement-water slurry is done off-site, the cement weigh hopper shall discharge directly into the mixer. If all mixing is done off-site either the weigh hopper shall discharge directly into the mixer or approved means shall be provided to transfer the cement for each batch from the weigh hopper to the mixer in enclosed containers so designed that loss or contamination will be prevented. Delivery of cement to the mixer shall be within a plus or minus two percent of the required weight.

9.2.2 Mixing water: An approved water measuring device shall be provided which will be capable of measuring the mixing water within the specified requirements for each batch. Measuring may be by weight or by volume. The mechanism for delivering water to the mixer shall be such that leakage will not occur when the valves are closed. The filling and discharge valves for the water batcher shall be so interlocked that the discharge valve cannot be opened before the filling valve is fully closed. Weighing units shall include a visible springless dial, which shall indicate the scale load at all stages of the weighing operation, or shall include a beam scale with a beam balance indicator. If water is measured by volume, the measuring equipment may be a batch-type volumetric measuring device or a metering device so designed that after each delivery the hands can be conveniently set back to zero. If a batch-type volumetric measuring device is used, it shall be equipped with an easy to read gage and with a readily adjustable overflow device which shall be operated to insure uniformity of batching operations. Any water batcher used shall discharge directly into the mixer. If the cement-water slurry is mixed off-site and additional water added at the final mixer, the requirements herein for batching mixing water shall apply equally at each mixing location. The delivery of mixing water to the mixer shall be within plus or minus two percent of the required weight or volume.

9.2.3 Foam: The preformed foam shall be generated in a generator wherein liquid foaming agent and water are subjected to the action of compressed air, in the proportions and at the pressure directed. The foam generator shall be of a type and make recommended by the manufacturer of the liquid foaming agent. The preformed foam shall be discharged from the generator directly into the mixer and the quantity shall be measured by timing the period of discharge. Control of the discharge of preformed foam from the generator shall be semi-automatic and shall be controlled by means of a readily adjustable timing mechanism which will automatically shut off the discharge at any preset time. The timing mechanism shall be equipped with an overriding manual control which will permit the addition of small amounts of extra foam to any batch when directed. Delivery of foam to the mixer shall be within a plus or minus two percent of the required amount. The liquid foaming agent and the water for generating foam shall be measured as directed when charging the foam generator. Deviations from this approach shall be subject to approval.

9.2.4 Slurry: If cement-water slurry is premixed, suitable facilities shall be provided at the final mixer for batching the cement-water slurry. Batching facilities shall be as approved and shall conform to the requirements specified in subparagraph 9.2.2 above for batching facilities for mixing water.

9.3 Mixing equipment and operation: The mixers shall be standard commercially available mixers subject to approval. Mixer capacity shall be adequate to meet the requirements of the planned work schedule. The mixers shall be capable of maintaining a uniform blade speed at all times and shall be operated at the blade speeds designated by the manufacturer on the name plate or as otherwise directed. The mixers shall be maintained in satisfactory operating condition, and mixer drums and blades shall be kept free of hardened concrete or grout. Mixer blades or rubber inserts shall be replaced when worn down more than ten percent of their depth. Suitable facilities shall be provided for readily and safely obtaining representative samples of slurry or foamed concrete from each mixer used before the mixer is discharged. Such facilities shall consist of a grated outlet located near the bottom of the mixer or other equally suitable facilities as approved. Each mixer shall be provided with a readily adjustable approved device to prevent discharge until the required mixing time has elapsed. The required maximum mixing times shall be as follows unless otherwise directed:

Mixing of cement-water slurry before addition of preformed foam - 4.0 min.
Mixing of foamed concrete after addition of preformed foam is complete - 5.0 min.

These required mixing times may be increased or decreased for any or all mixers during construction operations as determined by the Contracting Officer. Excessive overmixing will not be permitted. If cement-water slurry is premixed, any approved type of mixer may be used for this premixing operation; however, all specific requirements contained herein shall apply equally to the equipment and the operation thereof.

9.4 Communications: Telephone or some other satisfactory means of rapid communication between the final mixing and pumping site and the forms in which foamed concrete is being placed, and also the premixing site if two-stage mixing is used, shall be provided.

10. CONVEYING AND PLACING:

10.1 General: Foamed concrete shall be conveyed from the mixer to the forms at a rate of approximately 15 cubic yards of concrete per hour.

Operation of the pumps shall be such that a continuous stream of foamed concrete without air pockets is produced. If a two-stage mixing operation is used, the cement-water slurry shall be conveyed from the mixer used for premixing the slurry to the final mixer by approved means which will prevent loss, contaminations or alteration of the slurry. Cleaning of pipelines shall be by water only; use of compressed air is prohibited. If, during placement, it is desired to empty or partially empty the pipelines, either of cement-water slurry or foamed concrete, the procedures used shall be such that there is no contamination or alteration of the slurry or of the foamed concrete which is actually placed in the structure. All conveying and placing equipment and procedures shall be subject to approval and shall be modified when and as directed in order to produce the desired quality of in-place foamed concrete.

10.2 Equipment: Pumps used for pumping the foamed concrete shall be subject to approval and shall have the capability of producing the rate of concrete mentioned above, and meet the requirements of the planned work schedule. Pipelines may be of rigid pipe or flexible hose and shall be of adequate capacity and pressure capability, as approved. Maximum length and diameter of pipeline used for pumping foamed concrete shall be as approved.

10.3 Placing: Because of the exactness and preciseness necessary in this research project, the pouring of one fragmentation trap will not be done in one continuous pour. Fifty percent or less but not less than 30 percent of the total volume of the foamed concrete in one fragmentation trap shall be poured on one day. The remainder of the fragmentation trap shall be poured the following day.

10.4 Joints: The contractor shall arrange the pours so as to form only vertical cold joints.

11. PROTECTION AND REPAIR:

11.1 Protection: The contractor shall at all times protect the foamed concrete from damage of any kind. Workmen and equipment shall be excluded from contact with the foamed concrete until it has attained sufficient strength to withstand such traffic or loading, as directed. If desired by the contractor or if directed, the foamed concrete fragmentation traps shall be protected during subsequent construction operations with a covering of lightweight plywood or similar material.

11.2 Repair: Any areas of in-place foamed concrete which are determined by the Contracting Officer to be of inferior quality or to be so damaged as to be unsuitable shall be removed and replaced. Replacement shall be made in the same manner as original construction using the same type of material or shall be as otherwise directed. The contractor may be required to use a special patching mix containing material other than the original type of foamed concrete, particularly for small patches. All patching or replacement operations shall be as approved or directed.

12. <u>CURING</u>:

The only curing required for the foamed concrete will be application of membrane-forming curing compound to all exposed surfaces of foamed concrete fragmentation traps. Curing compound shall be applied to formed surfaces immediately after forms are stripped and to unformed surfaces at the time directed. Material used and method and rate of application shall be as directed. The integrity of the membrane shall be maintained for a reasonable period of time consistent with good engineering practices.