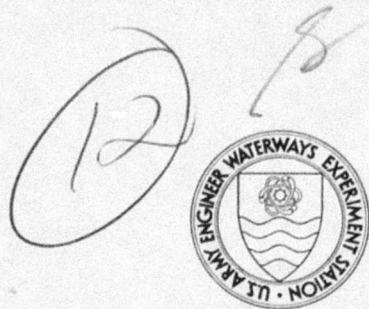




TECHNICAL REPORT C-75-2

A CONCEPT FOR RAPID REPAIR OF BOMB-DAMAGED RUNWAYS USING REGULATED-SET CEMENT

by

George C. Hoff

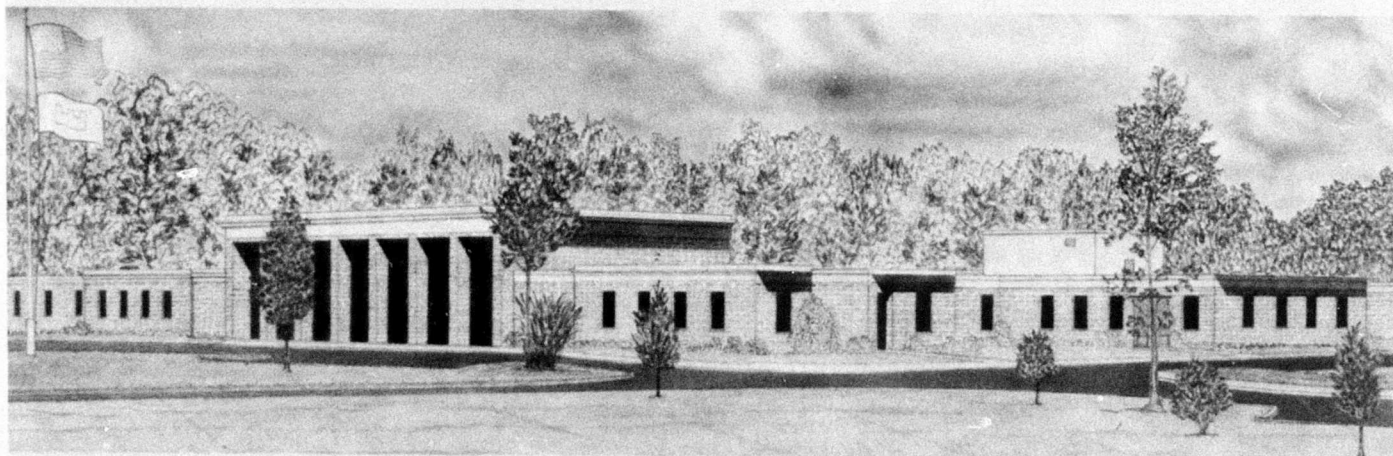
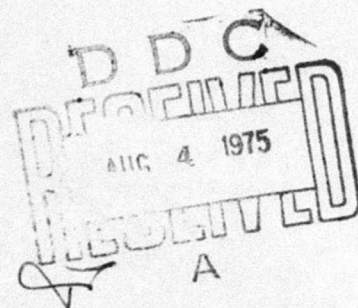
Concrete Laboratory

U. S. Army Engineer Waterways Experiment Station
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July 1975

Final Report

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20. ABSTRACT (Continued): *for 1113B*

be applied to make runways operational 4 hours from the start of the repair. The concept was evaluated by repairing a number of smaller craters using the equipment and procedures developed for the repair concept. The equipment consists of portable, continuous batching and pumping equipment. The evaluations indicated that the equipment possessed sufficient flexibility to repair everything from potholes to full-size craters. The regulated-set cement repair materials could be pumped several hundred feet with this equipment. The repaired surface was level with surrounding pavement surfaces. All regulated-set cement repairs are permanent and do not have to be upgraded or removed and replaced. When used as a subbase material, regulated-set cement cellular concrete can be proportioned to exceed the normal rigid-pavement bearing strength requirements. The early-age flexural strengths of regulated-set cement sanded mortars are adequate for use in rigid pavements. Implementation of the regulated-set cement repair concept reduces manpower requirements approximately 25 percent *25%* from ~~that required by~~ present repair procedures. The level of manpower skills required is similar to those presently used. Existing rapid-repair equipment kits would have to be modified for this concept but no new equipment development would be needed. Full-scale crater repairs are recommended for further evaluation of the concept. A sample specification for the continuous batching-pumping equipment is contained in Appendix A.

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PREFACE

The concepts and evaluations reported herein were developed primarily for the Air Force Weapons Laboratory, Kirtland Air Force Base, NM, as part of "Investigation of Regulated-Set Cement for Use in Rapid Repair of Bomb-Damaged Runways," during the period August 1971 to June 1973. The preparation of this report was authorized by the Office, Chief of Engineers, U. S. Army, under Military Engineering RDTE Project 4A762719AT31, "Research for Lines of Communication Facilities in Theater of Operations;" Task 002, "Air Line of Communication Facilities," Work Unit 005, "Development of Design and Construction Principles for Upgrading Deteriorated TO Pavements."

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Directors of WES during this study and the preparation of this report were BG E. D. Peixotto, CE, and COL G. H. Hilt, CE. Technical Director was Mr. F. R. Brown.

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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI)
UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
inches	25.4	millimetres
feet	0.3048	metres
square inches	6.4516	square centimetres
gallons (U. S. liquid)	3.785412	cubic decimetres
cubic feet	0.02831685	cubic metres
cubic yards	0.7645549	cubic metres
cubic feet per minute	0.02831685	cubic metres per minute
grams	0.001	kilograms
pounds (mass)	0.4535924	kilograms
tons (2000 pounds mass)	907.1847	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
pounds (mass) per cubic yard	0.59327638	kilograms per cubic metre
pounds (force)	4.448222	newtons
pounds (force) per square inch	0.006894757	megapascals
calories per gram	4184.000	joules per kilogram
Fahrenheit degrees	5/9	Celsius degrees or Kelvins ^a

^a To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

A CONCEPT FOR RAPID REPAIR OF BOMB-DAMAGED
RUNWAYS USING REGULATED-SET CEMENT

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Survivability of airfield runways after an attack greatly influences the ability of warring factions to achieve or maintain the tactical air superiority necessary to support the ground forces. The effectiveness of preemptive or retaliatory strikes against enemy airfields can quickly determine the outcome of a conflict, as was so vividly illustrated in the Middle East War of 1967. The need for air support is essential when both sides possess highly mobile ground armor units.

Airfields and, more specifically, runways under attack are usually not destroyed but are only rendered ineffective by the resultant munitions craters in them and the debris on them. If the damage to the runway can be repaired in a very short period of time, the runway has a high degree of survivability; if the repairs take a long time, the degree of survivability is greatly reduced. The U. S. Air Force has devoted a major effort to developing efficient techniques for repair of bomb-damaged runways under objective guidelines established by NATO. The U. S. Air Force has suggested that, for preliminary design purposes, a lane 50 feet¹ wide and 5000 feet long crossing three craters (Figure 1.1) formed by the explosion of 750-pound bombs 8 feet below the surface be repaired to make the runway operational. Current NATO repair criteria require the repair time not to exceed 4 hours. The repaired craters should be capable of supporting 16 passes of a single 29,000-pound, rolling wheel applied through a tire inflated to 300 psi (Reference 1).

The type and size of crater formed in the pavement generally depend

¹ A table of factors for converting U. S. customary units of measurement to metric (SI) units is given on page 5.

on pavement thickness, pavement subgrade, the size and type of munition, and its depth of penetration into the pavement and underlying subgrade (Reference 2). The U. S. Air Force has described craters as Types I, II, and III, as shown in Figure 1.2, based on depth of burst. A Type I crater (shallow depth of burst) is generally hemispherically shaped with widely spread debris but with no appreciable heaving or cracking in adjacent pavement. A Type II crater (intermediate depth of burst) is generally conical with widely spread debris; the adjacent pavement is cracked and heaved. Both Types I and II craters are partially filled with debris fallback that provides an apparent crater surface. The Type III crater (deep depth of burst) has a large cavity in the subgrade and from the pavement surface does not appear to be cratered at all. There is very little debris, but the adjacent pavement is cracked and heaved in large wedge-shaped sections. For repair purposes, the Type III crater can be transformed into a Type I or II shape using additional smaller detonations. The U. S. Army Corps of Engineers has refined the pavement crater description with classifications that range from Types 1-7 (Reference 3), as shown in Figure 1.3; a description of these craters is contained in Table 1.1.

A crater formed by the detonation of a 750-pound bomb 8 feet under the pavement surface is best described by the Air Force Type II or Corps of Engineers Type 3 craters. An actual cross section of a 750-pound bomb crater, shown in Figure 1.4 reveals the extent of upheaval and debris scattering (Reference 4). Figure 1.5 shows an actual crater and the area over which the debris is scattered. Figure 1.6 shows the crater interior. Figures 1.7, 1.8, and 1.9 show the type of debris that results and, in particular, the size of the displaced pavement pieces. A large, upheaved piece of concrete can be seen in Figure 1.8.

1.2 CURRENT REPAIR PROCEDURE

To fill the type of craters shown in Figure 1.4, the U. S. Air Force uses a method described in Reference 5. Briefly, the method consists of filling the crater with debris and compacting it (subgrade), placing and consolidating a select aggregate fill (base course), and finally placing

a landing mat system over the repair (wearing surface). The bomb-damage repair (BDR) kit, including all repair materials and equipment, is described in Reference 6 along with the number and type of personnel needed for the repair.

Immediately after an attack on the runway, a damage assessment team determines which craters are to be repaired to obtain the desired runway surface (Figure 1.1). Each repair team then separates into three groups--one group each for runway cleanup and crater filling, landing mat retrieval and assembly, and select-fill retrieval and transport. Two large front-end loaders (FEL's) are used on each crater to clear debris from undamaged runway around the craters (Figure 1.10). A grader and sweeper are used to clear an adjacent area for assembly of the landing mat (Figure 1.11). The two FEL's and a bulldozer push debris in the crater lip area into the crater (Fig. 1.12). As filling progresses, the bulldozer compacts debris in the bottom of the crater while simultaneously loosening and pushing up damaged pavement around the crater (Figure 1.13); these pieces of pavement are either pushed off the runway or back into the crater. Landing mat necessary to cover the crater is simultaneously assembled adjacent to the crater (Figure 1.14). The select fill is removed from stockpiles (Figure 1.15) and moved by dump truck to the crater where it is spread by a dozer and leveled and compacted by the grader. A final compaction is applied by a tractor-towed vibratory roller. The assembled landing mat is then pulled over the fill area and anchored; when this is completed for all three craters, the runway should be operational.

An approach similar to that described above can be used for smaller craters (Types 1 and 2, Figure 1.3). In these instances, the debris is not pushed back into the crater but is removed from the area. Depending on the crater size, the select-aggregate fill can be spread into the crater by the grader alone. However, the assembly of proper sized mats may be a problem in these cases.

1.3 OBJECTIVE

The present BDR technique is not without several inherent

disadvantages. It is difficult to sufficiently compact the rubble and debris in the crater. This operation requires a strong cap material (landing mat) which causes an elevated section in the pavement. The repair team requires 121 people for the three craters, of which 51 are needed solely for landing mat assembly (Reference 5). The potential BDR techniques and materials considered in the past to improve the present scheme have been quite numerous and are concisely summarized in Reference 1. The objective of this study is to present a concept for the rapid repair of bomb-damaged runways that eliminates the compaction problem and provides a level, structural wearing surface that allows the entire repair to be considered permanent rather than temporary. The number of personnel required for the repair is also reduced. The concept uses regulated-set cement as a binder material throughout the entire crater.

TABLE 1.1 U. S. ARMY CORPS OF ENGINEERS DESIGNATIONS OF BOMB CRATER TYPES IN PAVEMENTS AND THEIR CHARACTERISTICS (REFERENCE 3)

Crater Type	Crater Description	Bomb		Apparent Crater	True Crater	Rupture/Shear Zone (Surface Displacement)		Measures of Crater Damage		Bomb Impact Crater
		Small ^a	Large					Effective Debris Area	Camouflet	
1	Spall crater	Yes	Yes	No	Yes	No	No	No	No	No
2	Blow-out crater	Yes	Yes	Maybe	Yes	No	No	Yes	No	No
3	Standard crater	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No
4	Heave crater	Yes	Yes	Maybe	Yes	Yes	Maybe	Maybe	Maybe	No
5	Camouflet with spall crater	Yes	No	No	Yes	No	No	No	Yes	No
6	Camouflet with heave mound	Yes	Yes	No	No	No	No	No	Yes	Yes
7	Camouflet	Yes	No	No	No	No	No	No	Yes	Yes

^a Small bombs have explosive weights less than 50 pounds (23 kilograms TNT equivalent).

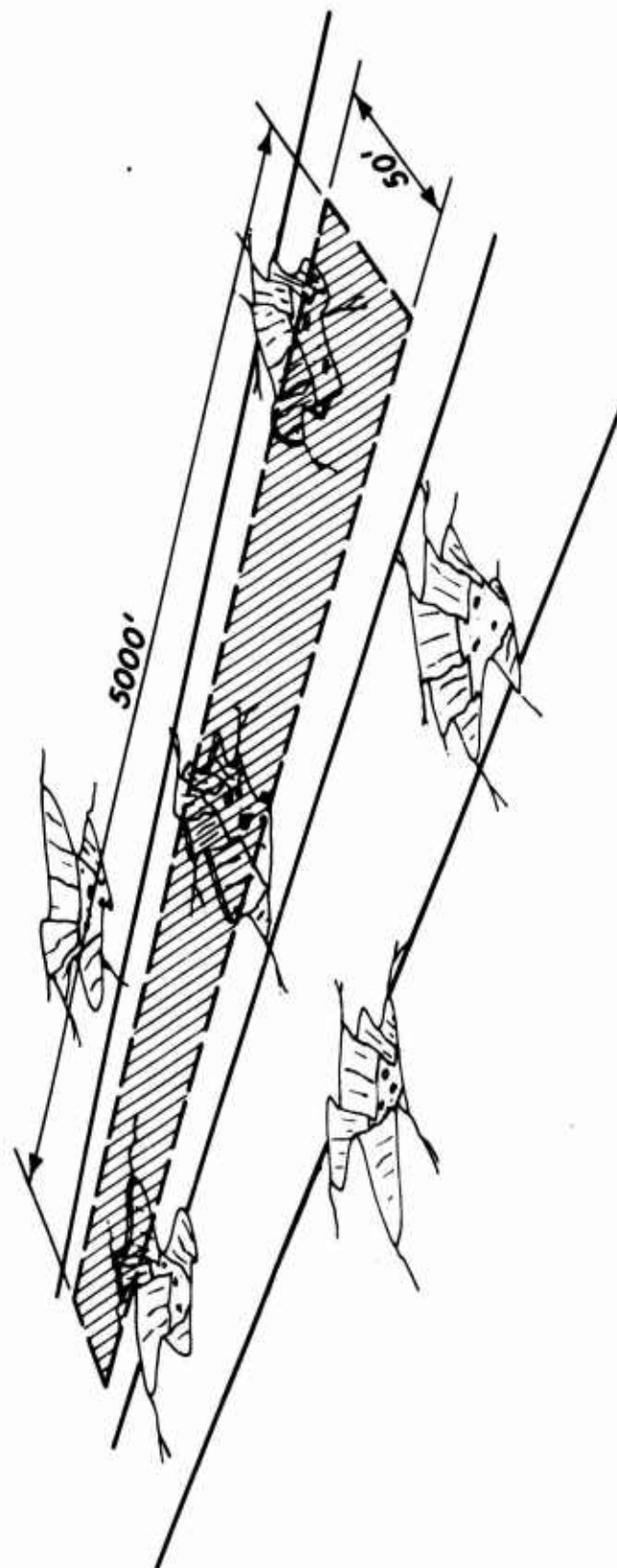


Figure 1.1 Required operational area on a bomb-damaged runway.

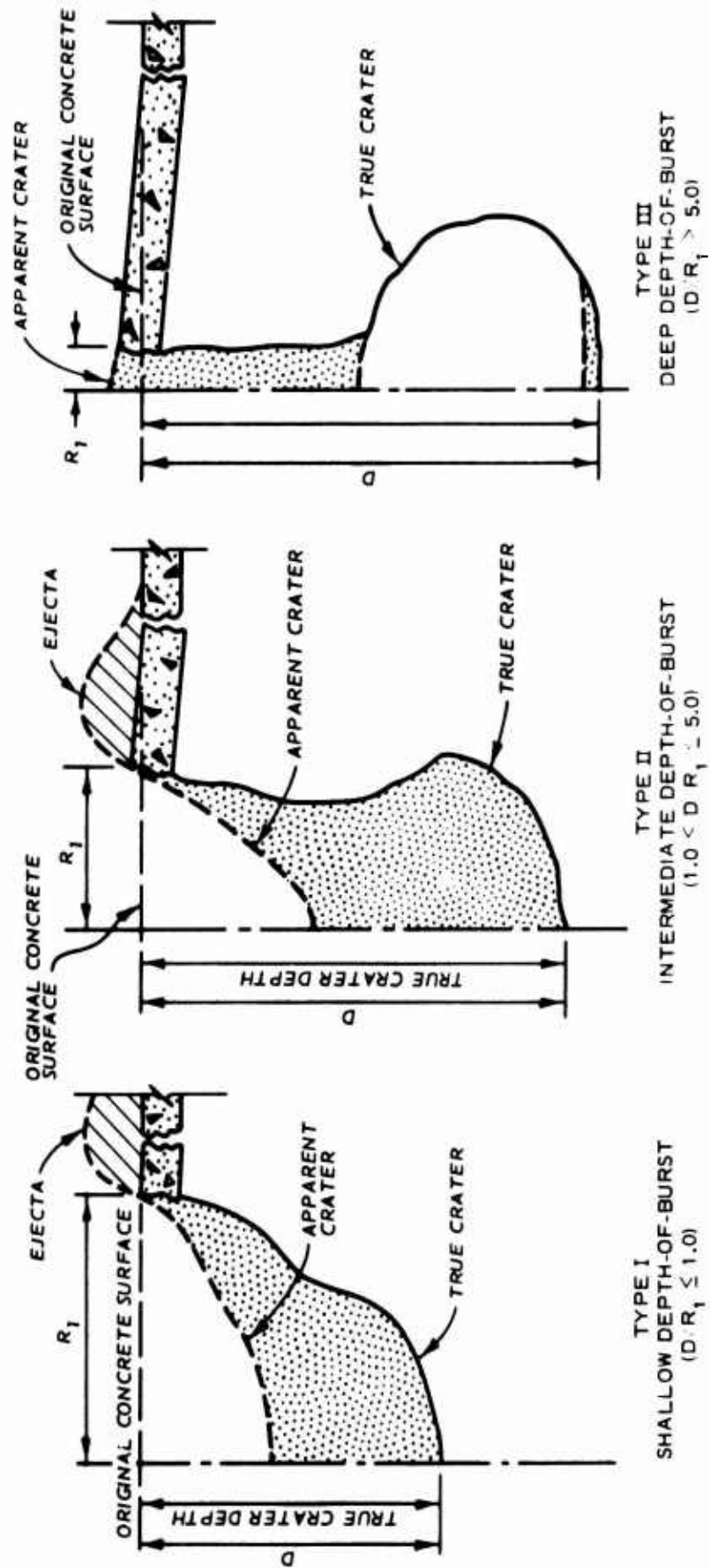
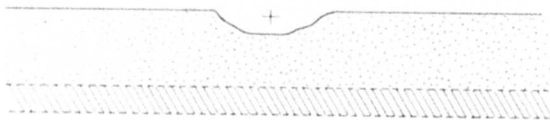
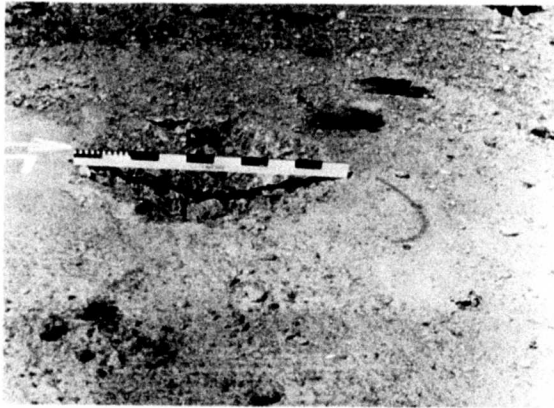


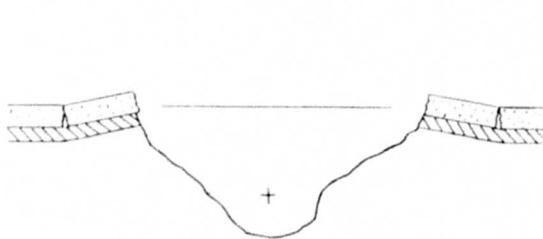
Figure 1.2 U. S. Air Force pavement crater classifications (Reference 2).



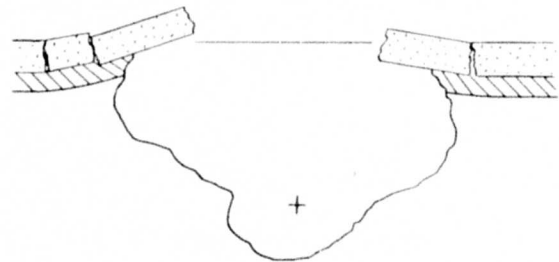
TYPE 1 - SLAB OR SPALL CRATER



TYPE 2 - BLOW-OUT CRATER

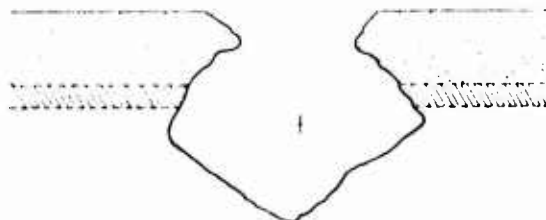


TYPE 3 - STANDARD CRATER

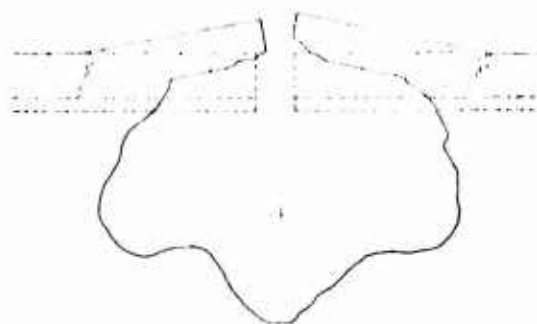


TYPE 4 - HEAVE CRATER

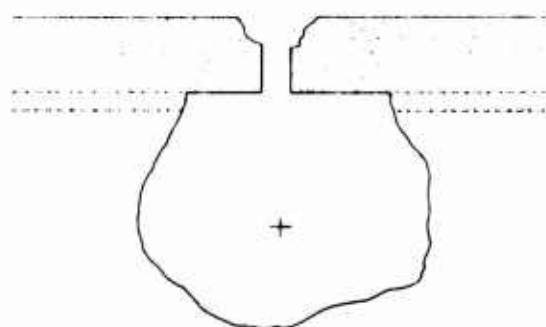
Figure 1.3 U. S. Army Corps of Engineers pavement crater classifications (Reference 3). True crater profiles are shown in and below pavements and subgrades (shaded areas). Depths of burst are indicated by small crosses (sheet 1 of 2).



TYPE 5 - CAMOUFLET WITH
SPALL CRATER



TYPE 6 - CAMOUFLET WITH
HEAVE MOUND



TYPE 7 - CAMOUFLET

Figure 1.3 (Sheet 2 of 2).

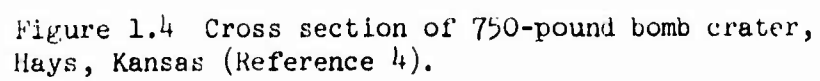




Figure 1.5 Crater and debris from a 750-pound bomb explosion.



Figure 1.6 The crater interior.



Figure 1.7 Debris on crater lip.



Figure 1.8 Close-up of crater lip debris.



Figure 1.9 Pieces of concrete pavement blown out by the explosion.



Figure 1.10 Cleanup of area around crater.



Figure 1.11 Sweeping adjacent area for
mat assembly.



Figure 1.12 Pushing debris into crater.



Figure 1.13 Removal of damaged pavement and compaction of debris in crater.



Figure 1.14 Mat surfacing assembly.



Figure 1.15 Select-fill stockpiles.

CHAPTER 2

REGULATED-SET CEMENT REPAIR CONCEPT

2.1 REPAIR PROCEDURES

The regulated-set cement repair scheme for craters in bomb-damaged runways is shown in Figure 2.1. The lower portion of the crater is filled with a combination of debris and neat (no aggregate) cellular concrete. This concrete, often referred to as foamed concrete, is made with regulated-set cement, water, and a preformed foam. It has a very high air content and low density and will flow readily around the debris dumped or pushed into the crater concurrently with cellular concrete during the filling of the crater. The crater is filled in this manner until it reaches a point approximately 3 feet from the desired top surface of the runway. At that point, no more debris is placed in the crater. The foam content, which is mostly air, of the concrete is reduced, and sand is added to the cellular concrete as aggregate. Bank-run sand and gravel could also be used providing the aggregate size was not so large that it could not be pumped with the type of pumps described in Section 4.6.5. These procedures increase the density and bearing strength of the cellular concrete. The filling operation continues using this cellular concrete containing aggregate to a point approximately 11-12 inches below the desired pavement surface. All preformed foam (or air) is then left out of the concrete, with the resulting cement, sand, and water composite providing the capping material which will function as the structural wearing surface. The capping material is placed to the desired level, screeded off, and finished, if desired.

The same type of approach can be used to repair spall or blow-out craters (Types 1 and 2, Figure 1.3); however, only the capping material would be used to repair spall craters, while the blow-out crater would require the sanded cellular concrete in the lower portion of the crater with the capping material on the surface; no debris would be used in a blow-out crater repair. Before the approach described above can be used for repair, heave craters and camouflet craters with heave mound

(Types 4 and 6, Figure 1.3) must be reshaped by mechanical means or explosives to resemble the Type 3 standard crater. In the camouflet and camouflet with spall craters (Types 7 and 5, Figure 1.3), no debris would be used, only the sanded cellular concrete in the lower portions of the crater with the capping material on the surface.

2.2 PROBLEMS IN REPAIRING CRATERS

The principal problems involved in the repair of a bomb crater in a concrete runway are:

1. Obtaining the required volume of material to fill the crater and construct the cap with a material of structural adequacy.
2. Obtaining a sufficient bearing capacity in the subgrade material within the time constraints of the repair.
3. Minimizing interference between debris cleanup operations and delivery of the fill material, both debris and cellular concrete, to the crater.

2.2.1 Crater Repair Volumes. Using the damage area shown in Figure 1.4 as a model of the standard crater for repair, a simplified crater approximating the Type 3 crater (Figure 1.3) in shape was developed as shown in Figure 2.2. It is assumed that, to obtain a satisfactory pavement surface after repair, all damaged pavement would have to be removed along with a small amount of base course (approximately 2 feet total in depth) to a point 35 feet from the center of the crater, thereby necessitating the replacement of a 70-foot-diameter section of pavement surface. In actual practice, the amount of damaged pavement to be removed is determined by using a straightedge to identify pavement rises that exceed an 11/16-inch rise in each 4 feet of horizontal distance; this pavement must be removed (Reference 6).

The maximum depth from the pavement surface to the surface of the apparent crater is assumed to be 12 feet. A triangular cross section for the apparent crater profile was used to obtain the volume of the subgrade portion of the crater. This volume plus the volume for the damaged pavement removal totals a repair volume of approximately 473 yd^3 of which 131 yd^3 would be the replacement of

an 11-inch-thick pavement surface. For repair purposes, the simplified crater is delineated into three zones as shown in Figure 2.3. Zone 1, the lower portion of the crater, will be filled by both debris and neat cellular concrete. Zone 2 will be repaired by sanded cellular concrete (no debris). Zone 3 is the capping material. Approximate volumes for Zones 1, 2, and 3 are 137, 205, and 131 yd³, respectively.

If all of the damaged pavement, some of its base course (2-foot combined thickness), and the debris piled on the damaged pavement were all pushed into the conical portion of the crater, it would overflow that portion even at optimum compaction of the debris. The problem is then not one of obtaining sufficient backfill material but of selective use, disposal, and consolidation of the debris in and around the crater.

2.2.2 Development of an Adequate Subgrade Material. The criteria for a BDR system applied immediately after an attack does not allow time for a critical evaluation of the in-place crater backfilling. There will not be time to evaluate the backfill to determine whether it has the proper subgrade modulus, or California Bearing Ratio (CBR) value. The presence of debris and rubble in the backfill would probably interfere with these evaluations even if they could be made. What, then, constitutes an adequate subgrade for the repair system and at which point during filling and compaction does it occur?

For expedient surfacing materials, such as landing mats, used on Short Airfield for Tactical Support (SATS) airfields, a subgrade CBR value of 10 is desirable, 6 is acceptable, and 4 is the design limit for AM-2 matting (Reference 7). A CBR value of 10 or more is usually obtained when the subgrade is not easily indented by a boot heel (Reference 8). For a more rigid type of surface, such as that contemplated herein, the necessary subgrade CBR value is affected by several factors, among them the strength and thickness of the surfacing material, the tire pressures, and the wheel loading. Using test data (over a CBR range from 2 to 10) smoothed to within 5 percent, the following empirical expression was developed for a tire pressure of 275 psi and a single-wheel loading of 29,000 pounds (Reference 9).

$$CBR = \left(\frac{290}{\sigma^{0.5} h} \right)^{3.546} \quad (2.1)$$

where

CBR = California Bearing Ratio, dimensionless

σ = flexural strength of pavement, psi

h = pavement thickness, inches

Another empirical expression has been developed to handle varying wheel loads and tire pressures (Reference 10):

$$CBR = \left(\frac{0.00281 P^{1/4}}{\sigma^{0.56} h} \right)^{4.545} \quad (2.2)$$

where

L = single wheel load, pounds

P = tire pressure, psi

In evaluating Equation 2.2, Beal and Chandler (Reference 8) found a better analysis for their data by dividing the subgrade CBR values into two groups: equal to or less than 10 and greater than 10. Pavement thickness was then expressed as:

$$h = \sqrt{\frac{L}{440}}, \quad CBR > 10 \quad (2.3)$$

and

$$h = 1.6 \sqrt{\frac{L}{440}}, \quad CBR \leq 10 \quad (2.4)$$

with the provisions that L be equal to or less than 30,000 pounds and that σ be equal to or greater than 400 psi. Regardless of the thickness calculated with Equation 2.3, no thickness less than 6 inches should actually be used. When σ is less than 400 psi, adjustments should be made to pavement thickness; however, the method of adjustment was not explained.

For this study, only the F-4E and F-111A aircraft will be

considered. They have maximum main-gear wheel loads and tire pressures of 27,000 pounds and 265 psi and 47,000 pounds and 150 psi, respectively (Reference 11). To compare Equations 2.1 and 2.2, assume $h = 11$ inches (Figures 2.2 and 2.3). At 3 to 4 hours age, fast-setting concretes can be expected to have flexural strengths of 150-400 psi. Using $\sigma = 200$ psi and the wheel loads and tire pressures for the F-4E,

$$CBR = \left(\frac{290}{\sigma^{0.5} h} \right)^{3.546} = 9.10$$

$$CBR = \left(\frac{0.0028LP^{1/4}}{\sigma^{0.56} h} \right)^{4.545} = 5.03$$

Since the CBR value is less than 10, Equation 2.4 suggests:

$$h = 1.6 \sqrt{\frac{27,000}{440}} = 12.5 \text{ inches}$$

which is within 14 percent of the assumed pavement thickness.

For the F-111A loading, Equation 2.2 produces

$$CBR = \left\{ \frac{[0.0028(47,000)(150)]^{1/4}}{(200)^{0.56} 11} \right\}^{4.545} = 32.7$$

If $\sigma = 400$ psi, $CBR = 5.6$.

This exercise is not intended to validate or refine Equations 2.1 through 2.4, but only to provide an indication of an acceptable CBR value. The F-111A loading appears to require the greatest CBR value, with Equations 2.1 and 2.4 being more conservative than Equation 2.2. For this program, a CBR value of 8 will be the required minimum in the subgrade under the rigid repair surface with a CBR of 10 being desirable. These values will keep pavement thicknesses to a reasonable value with regard to the amount of pavement material to be handled and placed and the amount of flexural strength developed by the capping material.

Figure 2.4 shows the development of a 1-hour-age bearing strength as defined by the CBR test (ASTM D-1883)² for neat cellular concretes of increasing density. This material does not contain debris as it would in the field. At densities of 50 pcf or greater, however, the effect of debris should not adversely affect the bearing strength of the composite fill material. Figure 2.5 shows the relationship between time after mixing and CBR for neat cellular concretes of the same cement content (800 lb/yd³) and water/cement ratio (0.55 by weight) but with different densities obtained by varying the air (or foam) content. Figure 2.6 shows the relationship between CBR at a 1-hour age and density for sanded cellular concretes. The bearing strength in all of these cases is more than adequate when using these materials in Zone 2 filling (Figure 2.3). Figure 2.7 shows the relationship of CBR and time for these concretes.

2.2.3 Minimizing Cleanup and Crater Filling Interference. To minimize interference during cleanup and filling of the crater, cellular concrete should be produced in an area some distance from the repair site. Cellular concrete is easily pumped using conventional positive-displacement or squeeze-type concrete pumps, and placing lines can be extended from the batching area to the repair site (Figure 2.8). Strategic location of the batching areas can facilitate multiple-crater servicing by each pump when the concrete demand at a given crater is reduced.

² American Society for Testing and Materials Standard Test Method.

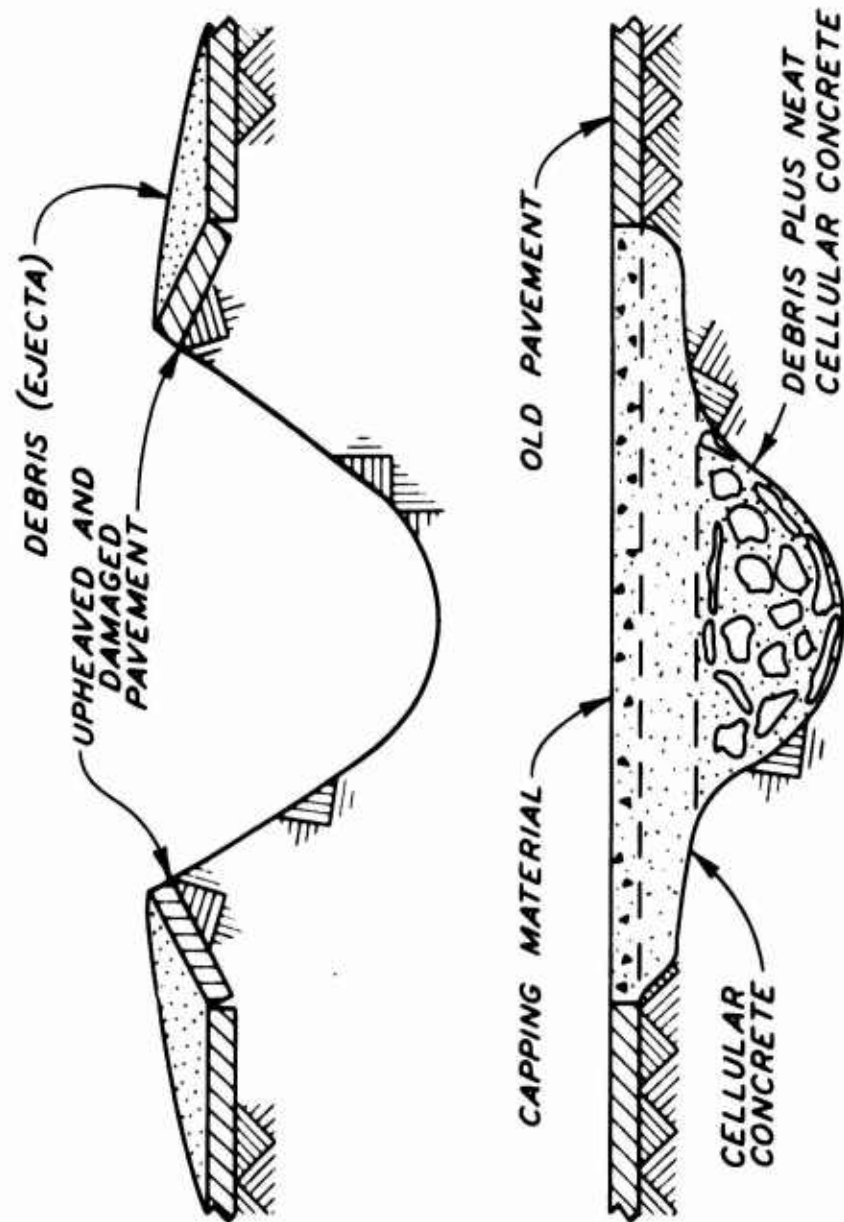


Figure 2.1 regulated-set cement repair scheme for bomb-damaged pavements.

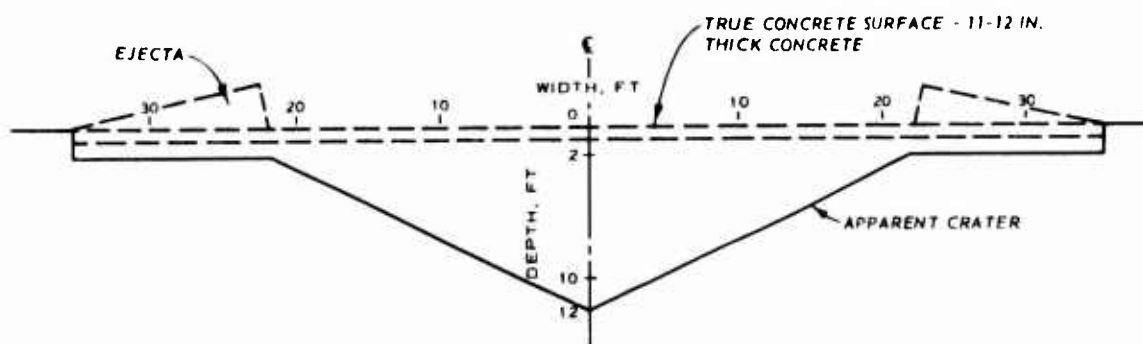
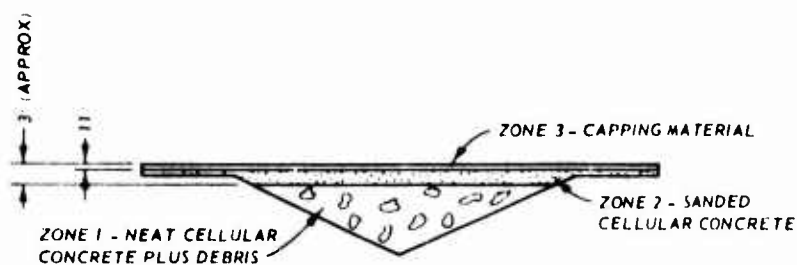


Figure 2.2 Simplified crater for repair.



ZONE 1 - BACKFILL	137 CU YD
ZONE 2 - SUBBASE	205 CU YD
ZONE 3 - STRUCTURAL CAP	131 CU YD
TOTAL	473 CU YD

Figure 2.3 Crater repair scheme plus volumes involved.

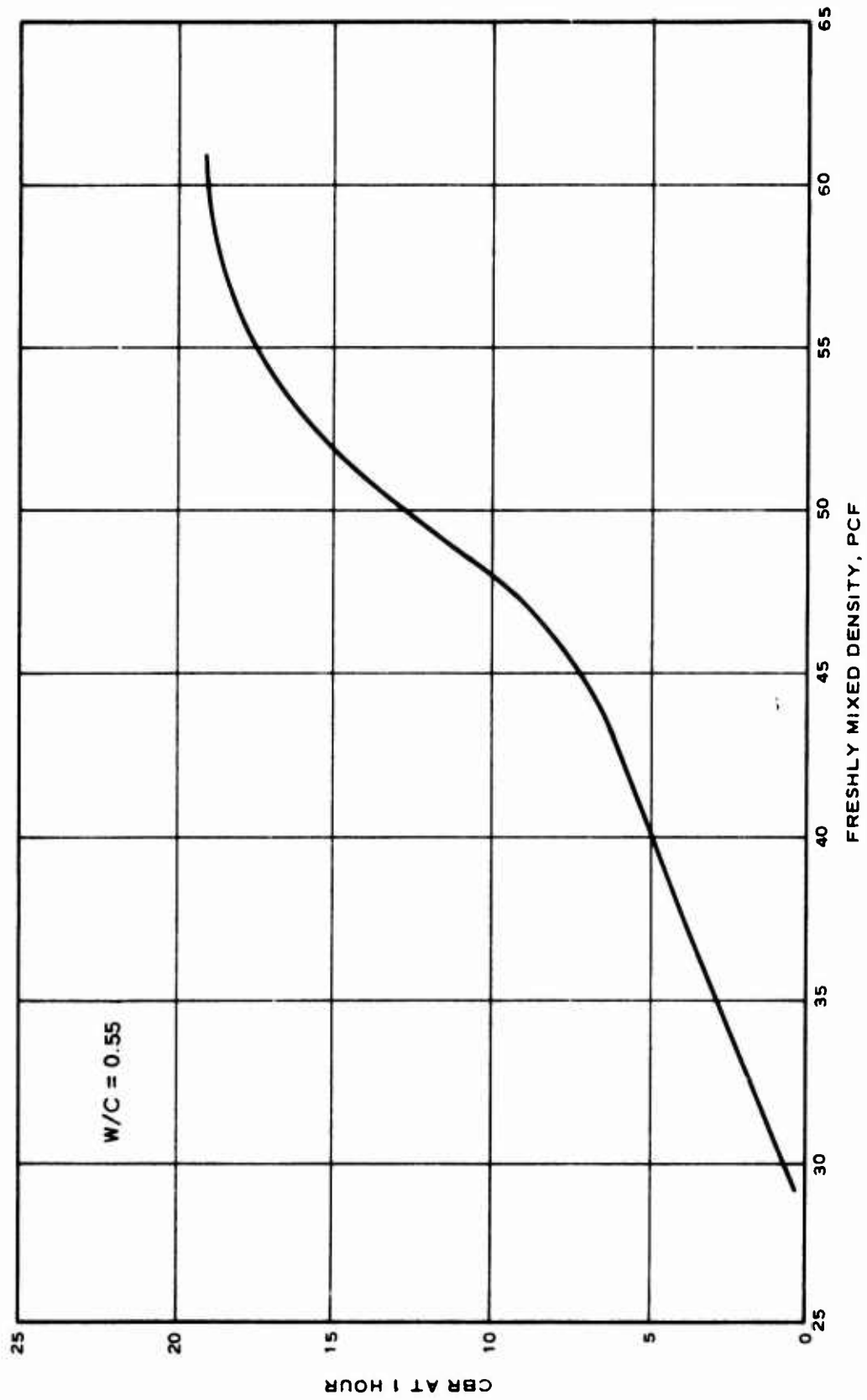


Figure 2.4 One-hour CBR value versus density for a neat cellular concrete.

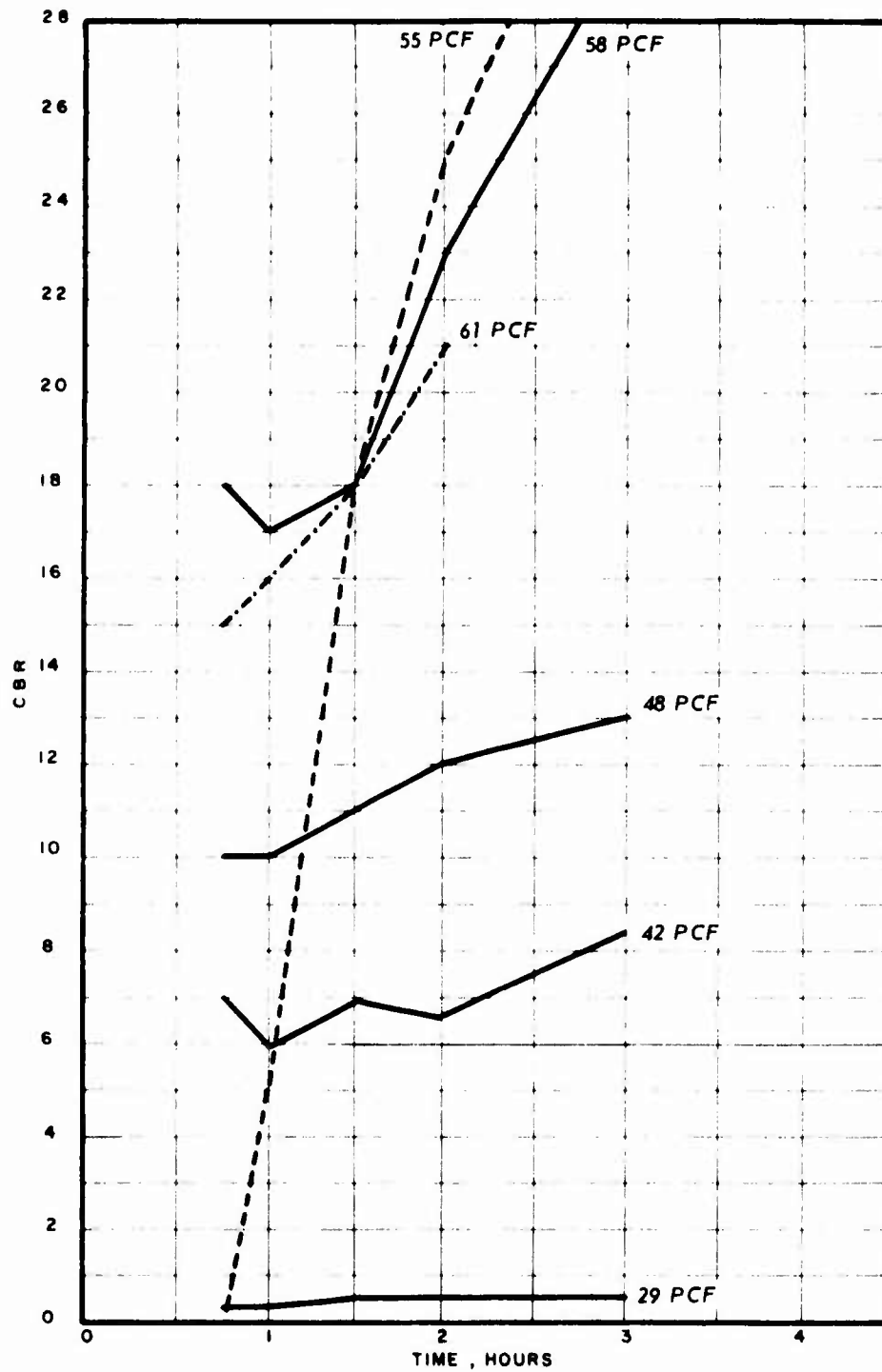


Figure 2.5 CBR value versus elapsed time for neat cellular concretes of various densities.

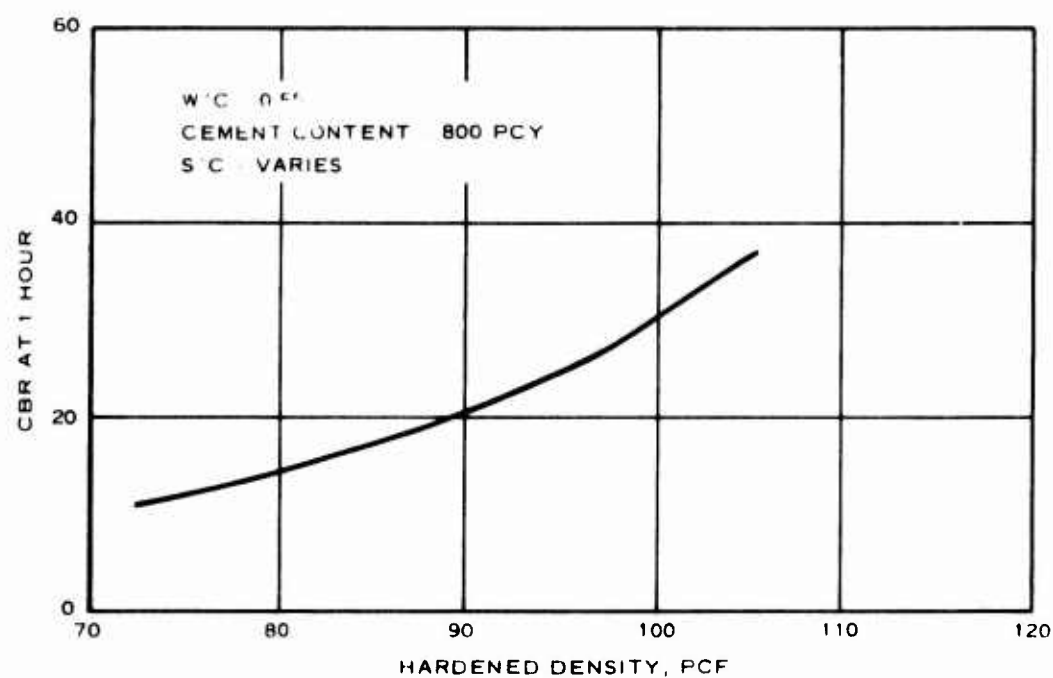


Figure 2.6 CBR at one hour versus density for sanded cellular concrete.

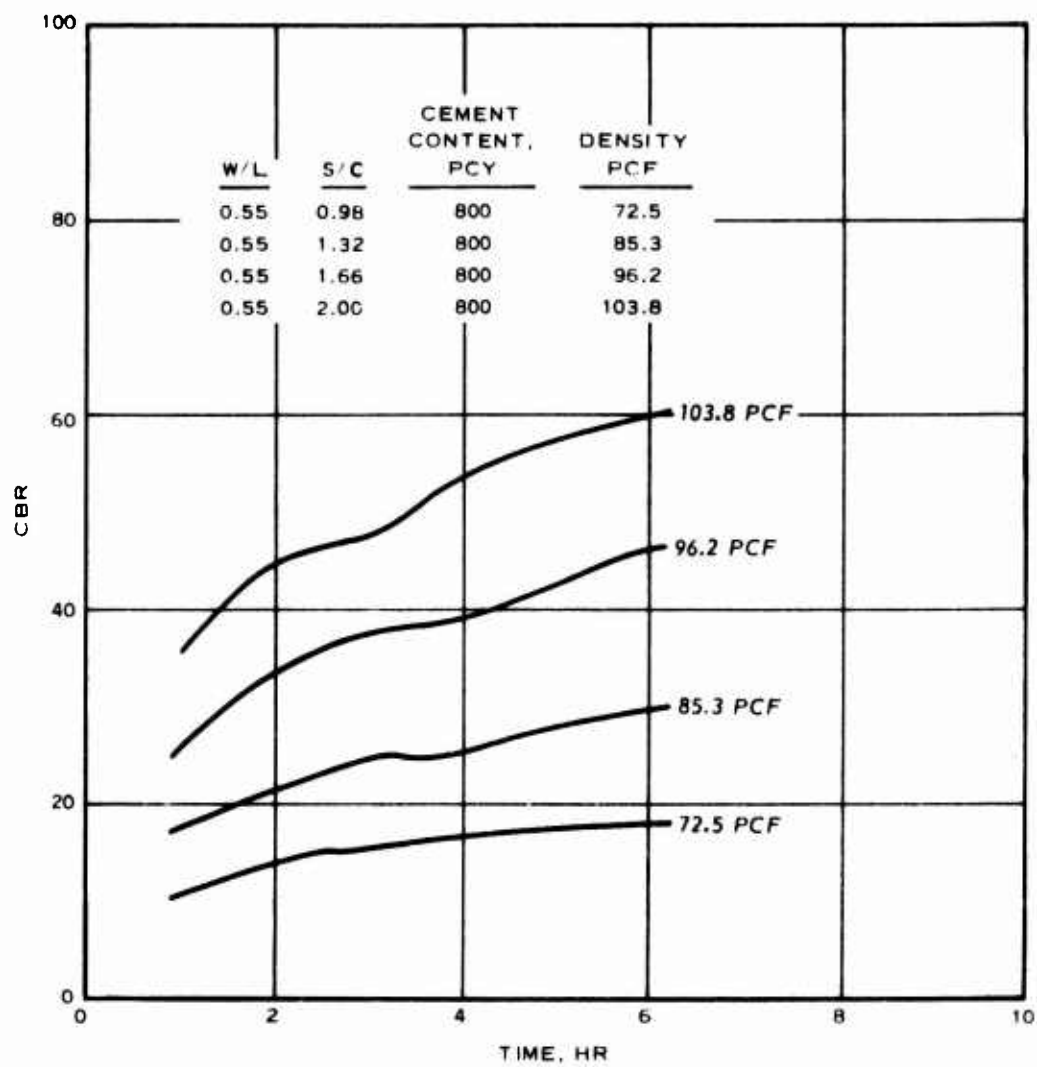


Figure 2.7 CBR versus time for sanded cellular concrete.

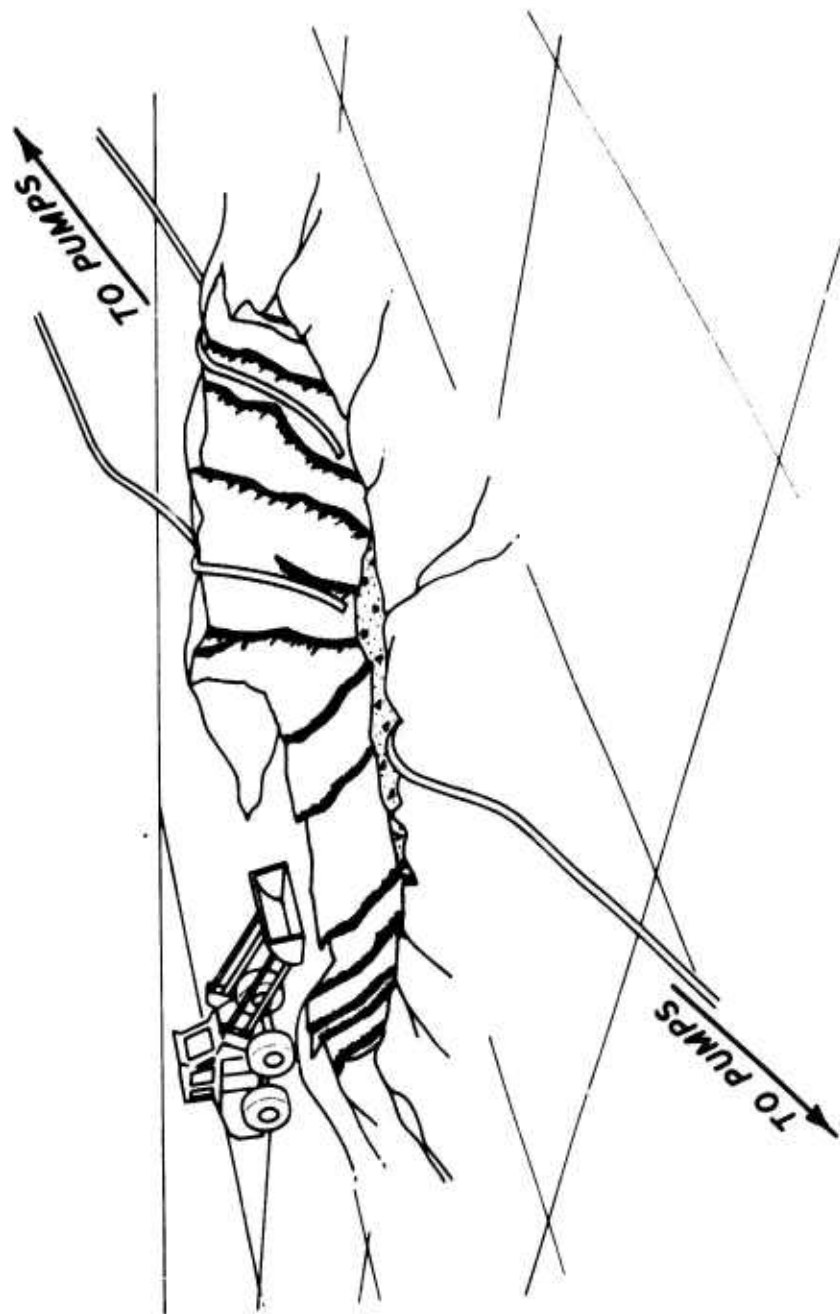


Figure 2.8 Concurrent filling of crater with debris and neat cellular concrete.

CHAPTER 3

MATERIALS FOR CRATER REPAIR

3.1 CELLULAR CONCRETE

Cellular concretes are lightweight concretes which contain stable air or gas cells uniformly distributed in the mixture. Other terms often used for cellular concrete are "foamed," "gas," "aerated," and "porous" concretes. These concretes may be made with or without the addition of natural or manufactured sand aggregate or mineral filler. Concrete densities can be varied from 15 to 140 pcf, depending on the proportioning of the constituents and the air content. References 12 and 13 summarize known information about these concretes over this density range.

Most of the physical properties of cellular concretes are related to density. Figures 3.1 (Reference 14) and 3.2 (Reference 13) are typical strength-density relationships for cellular concrete containing no aggregate and a sand aggregate, respectively. Densities are varied primarily by changing the air content of the concrete. The air cells in the concrete are usually added at the mixer as a stable, preformed foam resembling shaving cream. The foam is metered from a calibrated nozzle and is thoroughly blended into the mixture. The air cells may also be formed mechanically by entrapping air during high-speed mixing of concrete materials containing a foaming agent. It is also possible to form gas cells in the mixture as a product of a chemical reaction; this is generally a delayed reaction and occurs after the concrete is in place. The latter two techniques are not practical for operations such as rapid filling of craters because time constraints require minimal mixing and placing times.

Neat cellular concrete (no aggregate), when properly proportioned, has the consistency of a milk shake and flows readily into very small cracks and holes. This is a desirable feature for crater repair as the concrete will easily flow around and into the debris placed with it. When made with regulated-set cement, however, the cellular concrete

loses its flowability very rapidly as the cement begins to harden, and care must be exercised to place the debris and cellular concrete almost simultaneously to obtain the optimum intermingling of these materials.

3.2 REGULATED-SET CEMENT

Regulated-set cements are manufactured under patents issued to the Portland Cement Association (PCA) Skokie, Illinois, U.S.A. (Reference 15). At the beginning of this study (1970), five cement companies in the USA were producing the cement. Due to market uncertainties and shortages of conventional portland cement, four of these companies have, at the writing of this report, temporarily discontinued production of regulated-set cement. The PCA patent has been sold to Japan and the product is being produced by two Japanese companies. Other licensees for use of the PCA regulated-set cement patents exist in Australia, Canada, France, Germany, Great Britain, and South Africa, with patents pending in Austria, Indonesia, Italy, Korea, Mexico, Pakistan, Philippines, Spain, Taiwan, and Switzerland. A Thai regulated-set cement patent has also been sold to the Japanese. Regulated-set cement is also presently being produced in Germany and Austria.

Regulated-set cements, produced under the PCA patents, can be made to contain 1 to 30 percent by weight of a calcium haloaluminate having the formula $11\text{CaO} \cdot 7\text{Al}_2\text{O}_3 \cdot \text{CaX}_2$, in which X is a halogen; the cement can also be a blended cement produced by grinding together portland-cement clinker and a clinker containing a calcium haloaluminate. The halogen may be fluorine, chlorine, iodine, or bromine, but fluorine is preferred. Ordinarily, the sulfate content of these cements will be 1 to 12 percent SO_3 as calcium sulfate. U.S.A.-produced regulated-set cements average approximately 6 percent SO_3 , while Japanese productions average approximately 11 percent. Some typical chemical analyses for the cements are contained in Table 3.1.

In comparison with normal portland cement, regulated-set cement contains a reduced proportion of dicalcium silicate and no tricalcium aluminate. In the commercially available regulated-set cements, the tricalcium aluminate has been replaced by a new ingredient, calcium

fluoroaluminate. As with tricalcium aluminate, the hydration of fluoroaluminate imparts considerable strength to a paste or mortar immediately after it sets and also requires a retarder to control setting time. Both citric acid and calcium sulfate hemihydrate have been used as set retarders (Reference 16), but citric acid is most commonly used. The level of strength developed at early ages is somewhat proportional to the amount of fluoroaluminate contained in the cement as shown in Figure 3.3 (Reference 17). Approximately 20 percent calcium fluoroaluminate has been present in most cements marketed to date. Some typical strength development curves for ASTM C 109 mortars are shown in Figure 3.4; these curves represent four different cements. The cement which reached a cube strength of 6800 psi at 28 days age was the same cement that also reached 5300 psi. The only difference in the mortars was the higher strength mortar was retarded approximately 30 minutes using 0.2 percent citric acid by weight of cement. It should be noted that all the cements exceeded 800 psi in the first 3-4 hours.

The various cement companies that have manufactured regulated-set cement have done so according to their own specifications and not according to a national standard. Thus, the behavior and properties of regulated-set cement may vary according to the source of the cement. Figure 3.4 highlights the difference in cement properties depending on source; cements from four different producers were used in the same mixture proportions to produce these results.

3.3 SAND

In general, the sand should be clean, hard, sound, and durable and the sizes of particles should be graded within stated limits which are usually liberal. Many specifications for fine aggregate exist. If no military specification exists for sand to be used in bomb-damage repair, it is suggested that Federal Specification SS-A-281b, Aggregate; (For) Portland-Cement Concrete (also CRD-C 131, Reference 18) or CE 806.01, Guide Specifications for Military Construction, Concrete Pavements for Roads and Airfields, be used. Consideration should be given to the use of bank-run sand and gravel, if available, in lieu of

sand. However, because of pump limitations, nominal maximum aggregate size should not exceed 3/8 inch.

3.4 PREBLENDED MATERIALS

In view of the amount of materials to be handled during the repair, it may be advantageous to have the regulated-set cement and sand preblended before storage. A bagged mortar mixture product of this type complete with regulated-set cement is currently being marketed in this country. The preblending could be done at the producer's plant and shipped in bulk for storage.

3.5 PREFORMED FOAM

Preformed foam is produced by blending a foam concentrate, water, and compressed air in predetermined proportions and then passing this mixture through a device which violently agitates the solution (Figure 3.5). This mechanical system is commonly referred to as a foam generator. The agitation usually occurs in a foaming chamber or nozzle.

For use with normal portland cements, the foam concentrate must be of a chemical composition capable of producing stable foam cells in concrete which can resist the physical and chemical forces imposed during mixing, pumping, placing, and setting of the concrete. Change in concrete density during the time before the concrete sets is a measure of the stability of the foam. If the air cells in the foam are not stable, they begin to break down under mechanical manipulation and in the unhardened concrete, resulting in increases in concrete density and decreases in the yield of the concrete. Procedures for evaluating foam concentrates are presently being developed by the American Society for Testing Materials (ASTM).

A wide variety of materials have been used as foaming agents in concrete (References 19 and 20). In this country, two generic types of foaming agent, protein-based and detergent-based, have been developed into proprietary products which are widely used. Foams produced with these materials are compatible with portland cement and can remain in stable foam form for many hours. A typical chemical analysis of each

of these generic types used at the U. S. Army Engineer Waterways Experiment Station (WES) is as follows:

AD-465.³ The material as received was colorless and moderately viscous. The pH was 6.35, indicating a slight acid condition. Analysis of the infrared spectra generally classified it as a salt with a primary n-alkyl sulfate. Specifically, it was identified as an ammonium salt of a fatty alcohol sulfate; the alcohol was probably lauryl alcohol.

AD-469. The material as received was cloudy with a brownish-red cast, moderately viscous, and tacky. The pH was 7.5, indicating a slight alkaline condition. Analysis of the infrared spectra generally classified it as a protein degradation product that had been neutralized. This material was a derivative of aminocarboxylic acids. The spectra showed free carboxylate ions in addition to peptide bands (amide) and amino groups.

Proprietary foaming agents have been used in the production of regulated-set cellular concrete for roof deck insulation. In this application, the roof deck can be placed, worked upon, and covered in 1 day due to the hardening and strength characteristics of the cement; whereas, with a Type III, high-early-strength cement which is normally used, the decking operation cannot be completed in 1 day because of the time necessary for the concrete to harden and gain strength. With rapid-hardening and strength-gaining cements like regulated-set cement, it may be possible to use foams of lesser stability, such as fire-fighting foams, to produce cellular concrete because the cement will harden around the air cells before they have a chance to break down.

Before foaming, the foam concentrate is diluted with water to form a foam solution. The dilution rate depends on the foam concentrate used and the type of equipment used for the foaming. Dilutions of 2 to 8 percent concentrate are common. Most foam concentrate producers also produce generating equipment compatible with their product. Interchanging foam concentrates and equipment from different manufacturers will still produce stable foams, but the dilution rates may have to

³ WES materials identification number.

be adjusted to give comparable foams. The adjustment usually increases the amount of concentrate required. Some generating equipment, such as shown in Figure 3.6, are self-contained with the foam concentrate and water being proportioned automatically and continuously during operation of the equipment. For other units, such as shown in Figure 3.7, the foam solution must be mixed in an auxiliary tank from which the generating unit draws the solution.

Most commercial foam-generation equipment requires a compressed-air source, usually an auxiliary air compressor. The size of the compressor will depend on the generating unit, but most unit requirements will not exceed 80 psi and 15 cfm. The generator shown in Figure 3.7 does not require any compressor since it compresses its own air internally.

The foam solution and compressed air are blended in the hoses and in the foaming chamber or nozzle of the unit. The foaming chamber or nozzle is usually packed with discrete, randomly oriented elements which cause the flow of solution entering the chamber or nozzle to break up and become extremely turbulent and agitated, causing the solution to froth or "foam." Packings have included glass spheres, steel wool, split rings, and ceramic "noodles." The foam, as it discharges from the nozzle, has the consistency of shaving cream from aerosol cans.

Foaming chambers are usually immediately adjacent to the generating unit. The foam, in this case, is discharged from the chamber into a hose which carries it to a nozzle used to direct it into the concrete. Foaming nozzles are usually some distance from the generating unit. The foaming solution is forced from the generating unit through a hose to the nozzle, where it is foamed and directed into the concrete. The end result is the same in both instances. In both cases, the length of hose to the nozzle and the elevation of the nozzle over that of the generating unit affect the amount of backpressure the generating unit experiences. Changes in these factors can cause changes in foam density and foaming rate. Once a unit is calibrated, substantial changes during operation should be avoided if uniformity of foam is desired.

Preformed-foam densities can vary from 1.5 to 10.0 pcf, but 2 to 3 pcf is more common. Most foam concentrate producers state that a cubic

foot of foam solution will produce 20 to 30 cubic feet of foam. If the dilution rate of concentration is 4 percent and the expansion rate is 30, only 0.13 percent of the foam will actually be foam concentrate.

3.6 WATER

Water for mixing the concrete and producing the preformed foam should be free from injurious amounts of oil, acid, salt, alkali, organic matter, or other deleterious substances. Any oil in the water will severely reduce the ability of the foam to remain stable long enough for the cement to harden around it. Usually, water that is fit to drink is suitable to make concrete with. The most readily available water source near the runways should be investigated in accordance with Corps of Engineers Test Method CRD-C 406, "Method of Test for Compressive Strength of Mortar for Use in Evaluating Water for Mixing Concrete" (Reference 21), at routine intervals while the regulated-set cement repair scheme is in a state of readiness. Besides changes of strength due to the water, changes may occur in stiffening or handling time. If a source is unacceptable, the closest acceptable source should be investigated. All impounded waters should be checked as possible sources of mixing water since they would not be rendered inoperational when attacked as would be water delivery systems.

3.7 RETARDERS

Most proprietary retarders for portland-cement concrete will also retard regulated-set cement concrete. Some of these may not be compatible with the foaming agent in cellular concrete, however, and if considered for use, should be thoroughly investigated to establish whether a problem might exist. Citric acid ($\text{HOC}(\text{CH}_2\text{CO}_2\text{H})_2\text{CO}_2\text{H}$), however, has been shown as a highly effective retarder for regulated-set cement, and it has not given evidence of being incompatible with present-day foaming agents. Figure 3.8 shows the increases in handling time for a concrete achieved with just small amounts of citric acid (Reference 17).

Citric acid generally comes in a granular form but should not be

used in that manner. It is extremely soluble in water and should be dissolved in the mixing water or made into a concentrated citric acid solution which can then be metered into the water supply for the batching operation. When used in its dry granular form and blended with the cement during batching, it does not disperse uniformly throughout the mixture and can cause hardening problems.

3.8 MIXTURE PROPORTIONING

3.8.1 Absolute Volume Method. The proportioning of a preformed-foam cellular concrete begins with the selection of the desired density of the concrete, the cement content, and the water/cement ratio. For this study, a CBR value may be desired. The CBR and density relationship for a particular mixture must then be known (Figures 2.4 and 2.6) to determine the appropriate values. Various methods of proportioning (References 13, 14, 21, and 22) have been suggested, and all arrive at essentially the same proportions when used.

For this report, the proportioning method of absolute volumes will be used. The sum of the absolute volumes of cement (V_c), water (V_w), and aggregate (V_s) (usually sand) for 1 yd^3 of concrete subtracted from 27 ft^3 gives the volume of air (V_a) required per cubic yard of concrete.

$$V_a = 27 - (V_c + V_w + V_s) \quad (3.1)$$

The volume of air in foam depends on the density of the foam by the expression

$$V_f = \left(\frac{\gamma}{\gamma - d_f} \right) V_a \quad (3.2)$$

where

V_f = volume of foam

γ = unit weight of water = 62.3 pcf

d_f = density of foam, pcf

For foam densities of 2 to 3 pcf, the volume of foam required is

approximately 1.03 to 1.05 times that of air. The weight of water calculated from the cement content and water/cement ratio should be reduced by the weight of the foam which is considered as batch water.

In determining the mixtures to fill and cap the crater, calculations must be made for each repair zone in the crater because the requirements are different. Having once established the proportions for Zone 3, the amounts of cement and total water can remain the same for Zone 2 with just the sand and air content being changed to produce the desired density. As an example, consider the requirements for the capping material (Zone 3) as follows:

Water/cement ratio (by weight) = 0.55

Sand/cement ratio (by weight) = 3.00

Specific gravities:

Sand $\rho_s = 2.65$

Cement $\rho_c = 3.02$

Water $\rho_w = 1.00$

From the relationships of water and sand to cement,

$$W_w = k_1 W_c \quad (3.3)$$

and

$$W_s = k_2 W_c \quad (3.4)$$

where

W_w = weight of water, pounds

W_s = weight of sand, pounds

W_c = weight of cement, pounds

k_1 = water/cement ratio

k_2 = sand/cement ratio

Rewriting Equations 3.3 and 3.4 in terms of solid volume gives

$$V_w \gamma \rho_w = k_1 V_c \gamma \rho_c$$

or

$$V_w = k_1 \left(\frac{\rho_c}{\rho_w} \right) V_c \quad (3.5)$$

and

$$\left. \begin{aligned} V_s \gamma \rho_s &= k_2 V_c \gamma \rho_c \\ V_s &= k_2 \left(\frac{\rho_c}{\rho_s} \right) V_c \end{aligned} \right\} \quad (3.6)$$

The total no-air volume of a 1-cubic-yard mixture can be rewritten from Equation 3.1 as

$$V_c + V_w + V_s = 27 \text{ ft}^3$$

Then from Equations 3.5 and 3.6,

$$V_c + k_1 \left(\frac{\rho_c}{\rho_w} \right) V_c + k_2 \left(\frac{\rho_c}{\rho_s} \right) V_c = 27 \text{ ft}^3$$

or

$$V_c \left[1 + k_1 \left(\frac{\rho_c}{\rho_w} \right) + k_2 \left(\frac{\rho_c}{\rho_s} \right) \right] = 27 \text{ ft}^3$$

Substituting the values for specific gravities and ratios,

$$V_c \left[1 + 0.55 \left(\frac{3.02}{1} \right) + 3.00 \left(\frac{3.02}{2.65} \right) \right] = 27 \text{ ft}^3$$

$$V_c (6.080) = 27 \text{ ft}^3$$

$$V_c = 4.441 \text{ ft}^3$$

The Zone 3 quantities for a cubic yard of concrete are then easily calculated from the expressions and are as follows:

Cement	$4.441 \text{ ft}^3 \times 62.3 \text{ lb/ft}^3 \times 3.02 = 836 \text{ lb}$
Sand	$836 \text{ lb} \times 3.0 = 2508 \text{ lb}$
Water	$836 \text{ lb} \times 0.55 = 460 \text{ lb}$

A correction must be made in the water content to compensate for water in the sand. Assume the sand contains 2 percent free moisture. Most sand stored outdoors, except in arid regions, contains some free moisture.

Then:

$$2508 \text{ lb} \times 0.02 = 50.2 \text{ lb water}$$

The corrected water and sand are then:

$$\text{Water } 460 \text{ lb} - 50.2 \text{ lb} = 409.8 \text{ lb}$$

$$\text{Sand } 2508 \text{ lb} + 50.2 \text{ lb} = 2558.2 \text{ lb}$$

If the sand is dry and will absorb water, the corrections must be made with opposite sign. The actual Zone 3 quantities for a cubic yard of material are as follows:

Cement 856 lb

Sand 2558 lb

Water 410 lb

The theoretical density for the Zone 3 material is 140.8 pcf.

To modify this for use in Zone 2, the quantities of cement and water can be left the same, but the sand must be changed and air added in the form of foam. Assume a cellular concrete density of 100 pcf is needed to provide the subgrade strength. The foam density is 3.0 pcf. The total batch weight for 1 yd³ is then

$$27 \text{ ft}^3 \times 100 \text{ lb/ft}^3 = 2700 \text{ lb}$$

The following calculation can then be made:

	<u>Weights</u>	<u>Absolute Volume</u>
Cement	$836 \text{ lb} \times \frac{1}{3.0 \times 62.3 \text{ lb/ft}^3}$	$= 4.441 \text{ ft}^3$
Water	$460 \text{ lb} \times \frac{1}{1.0 \times 62.3 \text{ lb/ft}^3}$	$= 7.376 \text{ ft}^3$
Total	1296 lb	11.817 ft ³
Dry sand required:		
	$2700 \text{ lb} - 1296 \text{ lb} = 1404 \text{ lb} \times \frac{1}{2.65 \times 62.3 \text{ lb/ft}^3}$	$= 8.504 \text{ ft}^3$
Absolute volume of cement, water, and sand		$= 20.321 \text{ ft}^3$
Air volume required = $27.000 \text{ ft}^3 - 20.321 \text{ ft}^3 = 6.679 \text{ ft}^3$		

$$\text{Foam volume} = \left(\frac{62.3}{62.3 - 3.0} \right) \frac{\text{lb}}{\text{ft}^3} \times 6.679 \text{ ft}^3 = 7.017 \text{ ft}^3$$

$$\text{Water in foam} = 3.0 \frac{\text{lb}}{\text{ft}^3} \times 7.017 \text{ ft}^3 = 21.0 \text{ lb}$$

$$\text{Water in sand (assume 2 percent)} = 0.02 \times 1404 \text{ lb} = 28.1 \text{ lb}$$

$$\text{Corrected water} = 460 \text{ lb} - 21.0 \text{ lb} - 28.1 \text{ lb} = 410.9 \text{ lb}$$

$$\text{Corrected sand} = 1404 \text{ lb} + 28.1 \text{ lb} = 1432.1 \text{ lb}$$

The final Zone 2 quantities for 1 cubic yard are then

Cement	836 lb
Sand	1432 lb
Water	411 lb
Foam	7.017 ft ³

If the discharge rate of the foam nozzle is known, the amount of foam discharge required in units of time can be determined. Assume the nozzle discharges at a rate of 12 cfm, then:

$$\frac{7.017 \text{ ft}^3}{12 \text{ ft}^3/\text{min}} \times 60 \frac{\text{sec}}{\text{min}} = 35.1 \text{ sec}$$

Depending on the foam concentrate and cement used and the mixing and placing equipment and techniques used, the actual air content of the concrete at the point of placement may be more or less than that included in the design; this will be reflected in the freshly mixed density. Adjustments for this difference, once it is known, can be readily made in the proportions by adjusting the foam time and water. Once the feed rates for cement and water are established for Zone 2, they can remain the same for the Zone 3 placement with the foam feed then being terminated and the sand feed rate increased.

The quantity determinations are more simplified for Zone 1 than for Zones 2 and 3. As an example, consider the requirements of a neat cellular concrete of 50-pcf density at a water/cement ratio of 0.55. Assume the foam concentrate to be part of the total water in the mixture.

Total batch weight = $27 \text{ ft}^3 \times 50 \text{ lb/ft}^3 = 1350 \text{ lb}$. The total batch weight consists only of the weight of the cement and water, hence

$$W_c + W_w = 1350 \text{ lb}$$

From the water/cement ratio relation (Equation 3.3),

$$W_c + 0.55 W_c = 1350 \text{ lb}$$

or

$$W_c = 871 \text{ lb}$$

and

$$W_w = 479 \text{ lb}$$

The volume of air required in the mixture is then determined from Equation 3.1.

$$\begin{aligned} V_a &= 27 - (V_c + V_w + V_{agg}) \\ &= 27 - \left(\frac{W_c}{\gamma \rho_c} + \frac{W_w}{\gamma} + 0 \right) \\ &= 27 - \left[\frac{871}{(62.3)(3.02)} + \frac{479}{(62.3)} \right] \\ &= 27 - (4.629 + 7.689) \\ &= 14.682 \text{ ft}^3 \end{aligned}$$

From Equation 3.2

$$\begin{aligned} V_f &= \left(\frac{62.3}{62.3 - 3} \right) 14.682 \text{ ft}^3 \\ &= 15.425 \text{ ft}^3 \end{aligned}$$

The weight of the foam is then

$$\begin{aligned} W_f &= 15.426 \text{ ft}^3 \times 3.0 \text{ lb/ft}^3 \\ &= 46.3 \text{ lb} \end{aligned}$$

The corrected water is then

$$479 \text{ lb} - 46.3 \text{ lb} = 432.7 \text{ lb}$$

The actual quantities for a 1-cubic-yard batch in Zone 1 are then:

Cement	871 lb
Water	433 lb
Foam	15.425 ft ³

Using the same foam-generator discharge rate as before, 77.1 seconds of foam would be needed in the 1-cubic-yard batch. Again, adjustments may have to be made in foam content once pumping begins to compensate for small density changes occurring during pumping.

3.8.2 Nomographs. The crater will be actually repaired in a stress situation in which the time for calculations such as those shown in Section 3.8.1 will be minimal, if any time is available at all. In these circumstances, the individual in charge of the repair should know in advance which densities of concrete are needed in the various parts of the crater, which water-cement ratio should be used, the density of the preformed foam, and the discharge rate of the foam generators. With this information, and a nomograph (Figure 3.9), the quantities of materials needed can be determined in a few seconds.

The nomograph in Figure 3.9 is based on the absolute volume proportioning method and is for a cement with a specific gravity of 3.02. Small changes in this value will not significantly affect the values of weights and volumes obtained. Some curve smoothing was used to obtain the foam-density lines. The nomograph will provide the information needed to make the neat cellular concrete for the Zone 1 (Figure 2.3) filling. An additional nomograph would be needed for the Zones 2 and 3 material requirements because of the sand requirement. The following step-by-step procedure and work sheet for using the nomograph is recommended:

1. Record the density of concrete needed, the water/cement ratio desired, the density of the preformed foam, and the discharge rate of the preformed foam from the generator.

Freshly mixed density = _____ pcf

Water/cement ratio = _____

Preformed foam density = _____ pcf

Foam generator discharge rate = _____ cfm

2. Draw a straight line from ①, the density of the concrete, through ②, the water/cement ratio, until it intersects ③, the weight of the cement in a cubic yard of concrete.

Weight of cement = _____ lb

3. From Step 1, use the known freshly mixed density to obtain the total weight of a cubic yard of cellular concrete from the table above ④.

Total weight of concrete = _____ lb/yd³

4. Draw a straight line from ③, the weight of cement (Step 2), through ④, the total weight of concrete (Step 3), until it intersects ⑤, the total weight of water in the concrete.
5. Proceed from the intersection on ⑤ along a horizontal line until intersecting ⑥, the density of the preformed foam. Interpolate between lines for foam densities not shown. The value of weight of added water ⑦ indicated at this point is the amount of water actually added to the cement.

Weight of added water = _____ lb

6. Continue along the horizontal line from ⑤ until reaching the vertical line value of concrete density from Step 1. Obtain the volume of foam ⑧ at this point from the inclined lines.

Uncorrected foam volume = _____ cu ft

7. From the table above ⑧, multiply the appropriate foam volume correction value based on foam density (Step 1) times the value in Step 6. This will give the actual foam volume needed.

Uncorrected foam volume × correction factor
= _____ cu ft of foam needed

8. Foam time for a cubic yard of cellular concrete is the actual foam volume (Step 7) times the discharge rate of the foaming equipment.

Foam volume, cu ft, × discharge rate, cfm, = _____ min

9. Set feed rate on equipment to deliver the following amounts of material to produce a cubic yard of cellular concrete.

From Step 3, weight of cement = _____ lb

Step 5, weight of added water = _____ lb

Step 8, foam time = _____ minutes or seconds

TABLE 3.1 CHEMICAL ANALYSES OF REGULATED-SET CEMENTS

Constituents	Japanese Cements				Refer- ence 24 A	U.S.A. Cements				WFS Data									
	Refer- ence 16		Refer- ence 23			Reference 24		RC 638		RC 651		RC 650		RC 663(2)		RC 663(3)		RC 663(L)	
	A	B	A	B		Huron, 3	General	Lone Star	General	General	Louisville	Huron	Huron	Huron	Huron	Huron	Huron		
SiO ₂	13.7	13.9	14.2	14.2	14.7	14.8	16.7	16.0	17.1	16.1	16.1	16.1	16.1	15.2	15.0	15.0	14.1	14.1	
Al ₂ O ₃	10.8	11.0	10.1	10.1	9.0	10.3	11.3	8.6	10.4	9.3	9.3	9.4	9.4	9.7	10.2	10.2	11.5	11.5	
Fe ₂ O ₃	1.7	1.7	1.7	1.7	2.4	2.3	1.0	1.8	0.9	1.7	1.7	1.7	1.7	2.4	2.1	2.1	3.3	3.3	
CaO	58.6	58.9	58.6	58.6	58.5	58.8	61.1	57.0	60.9	57.5	57.5	57.6	57.6	59.5	58.1	58.1	57.8	57.8	
MgO	0.7	0.8	1.0	1.0	1.5	1.9	0.9	1.3	1.0	2.9	2.9	2.8	2.8	0.9	1.9	1.9	1.6	1.6	
SO ₃	11.0	11.1	10.9	10.9	6.6	5.8	6.0	9.4	6.0	6.2	6.2	6.1	6.1	5.6	6.2	6.2	5.2	5.2	
Ignition loss	1.0	0.2	1.0	1.0	3.9	3.9	3.0	3.1	2.7	4.8	4.8	5.0	5.0	3.4	4.4	4.4	3.8	3.8	
Total	97.5	97.6	97.5	97.5	96.6	97.8	100.0	97.2	99.0	98.5	98.5	98.7	98.7	95.4	97.7	97.7	97.3	97.3	
Insoluble residue	NG ^a	NG	0.49	0.49	1.07	0.80	NG	0.26	0.3	1.39	1.39	1.18	1.18	0.77	1.11	1.11	0.75	0.75	
Na ₂ O	0.6	0.6	0.45	0.45	0.90	NG	NG	1.31	0.64	0.85	0.85	0.64	0.64	0.44	0.44	0.44	0.64	0.64	
K ₂ O	0.4	0.4	0.40	0.40	1.20	NG	NG	0.44	0.16	0.20	0.20	0.19	0.19	0.98	0.98	0.98	0.95	0.95	
Total alkalis as Na ₂ O	0.9	0.9	0.71	0.71	1.68	NG	NG	1.60	0.80	0.98	0.98	0.77	0.77	1.08	1.08	1.08	1.27	1.27	
F	0.9	1.0	1.40	1.40	0.74	NG	NG	NG	NG	NG	NG	NG	NG	NG	1.13	1.13	1.09	1.09	

^a NG denotes not given.

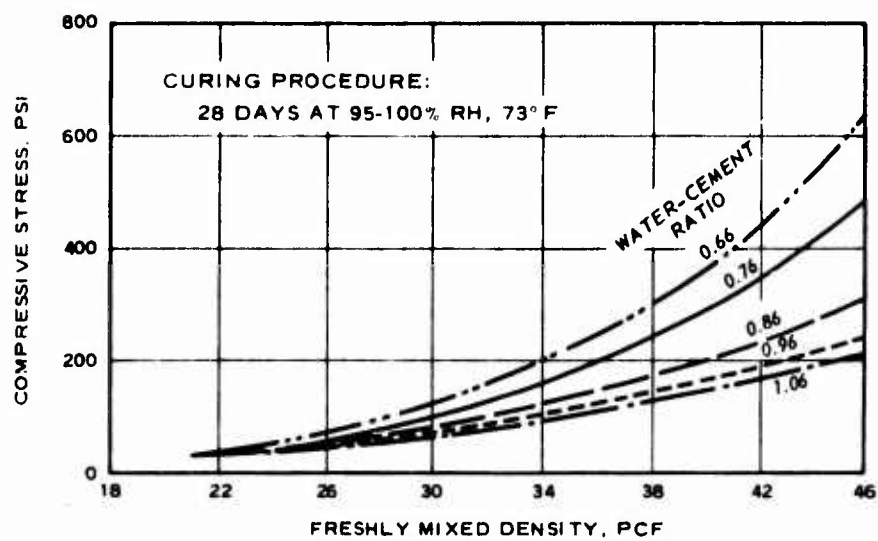


Figure 3.1 Strength versus density for a neat (no aggregate) cellular concrete (Reference 14).

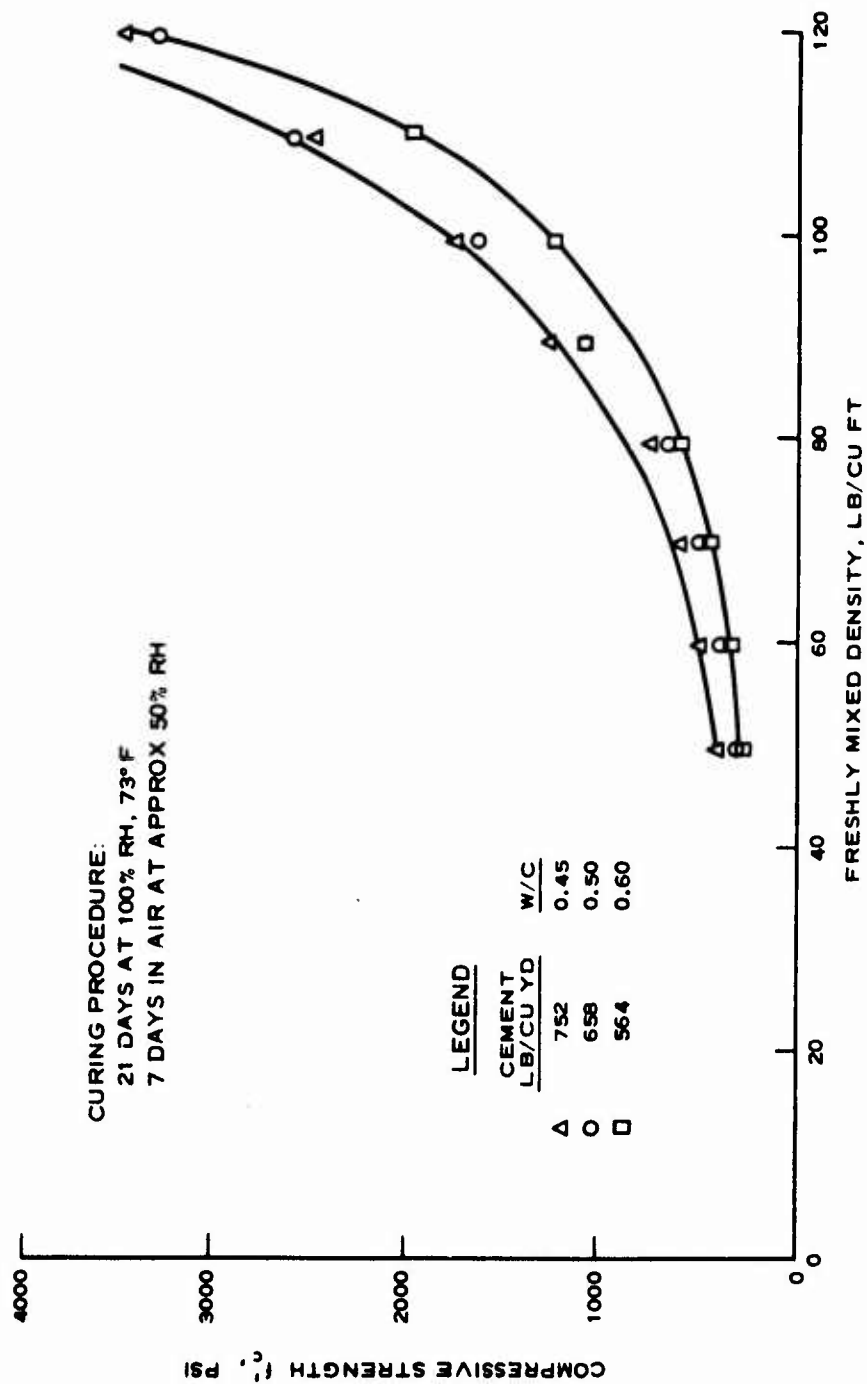


Figure 3.2 Strength versus density for sanded cellular concretes (Reference 13).

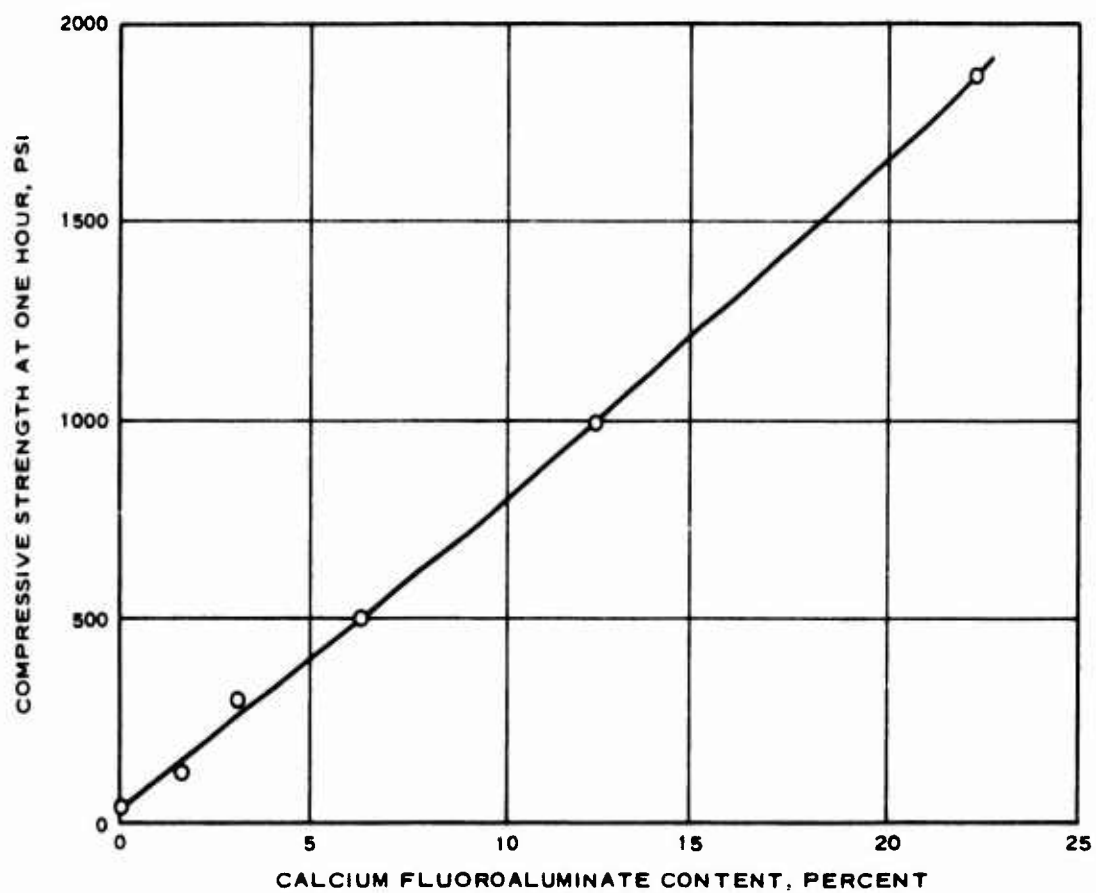


Figure 3.3 Influence of calcium fluoroaluminate content on 1-hour strength (Reference 17).

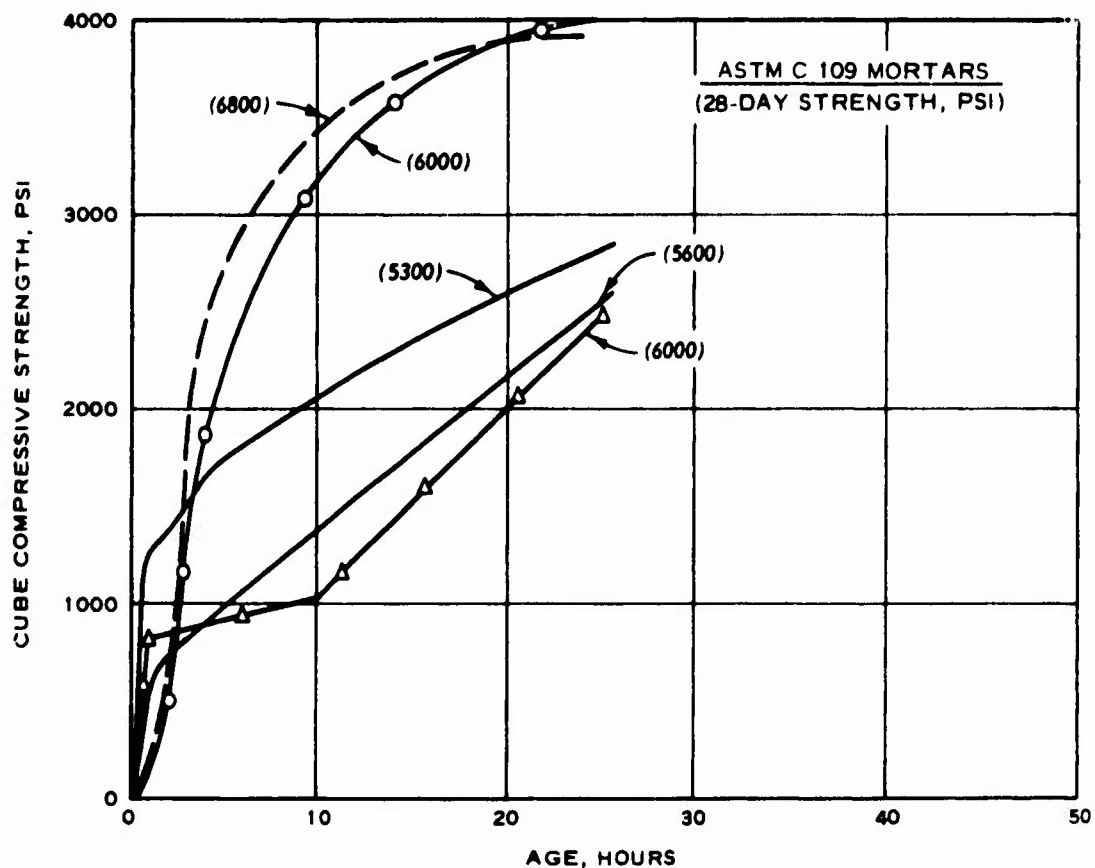


Figure 3.4 Compressive strength versus age for regulated-set cement mortars.

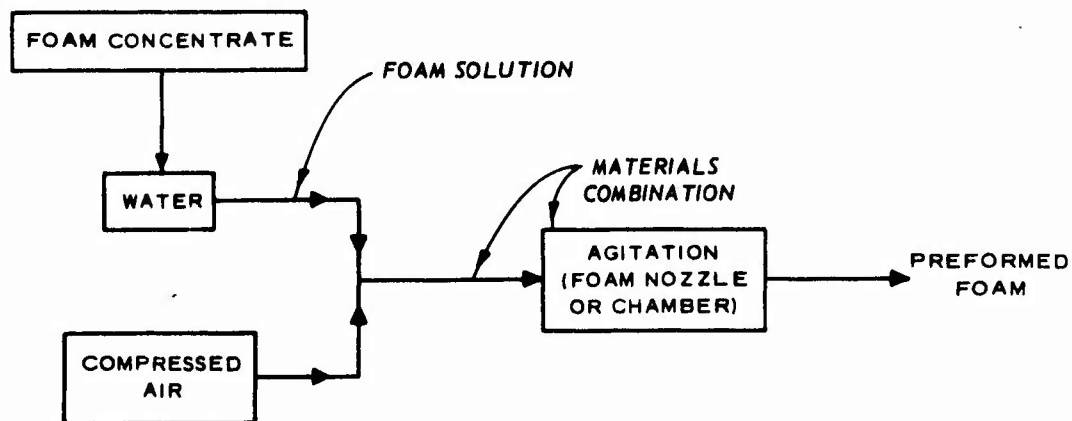


Figure 3.5 Preformed foam generation system.

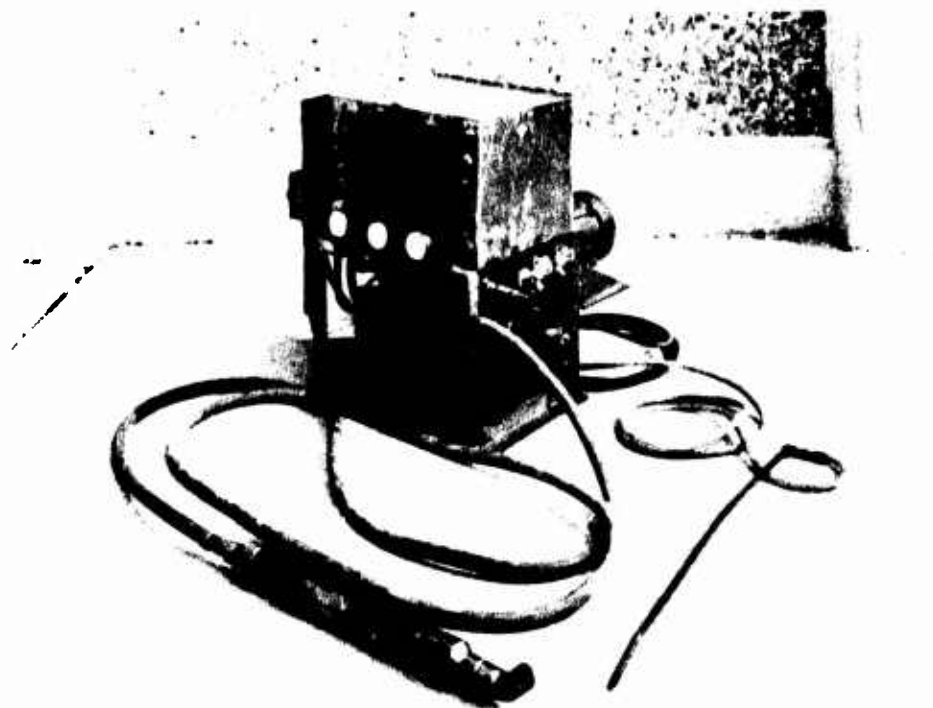


Figure 3.6 Automatic proportioning foam generator requiring a compressed-air source.

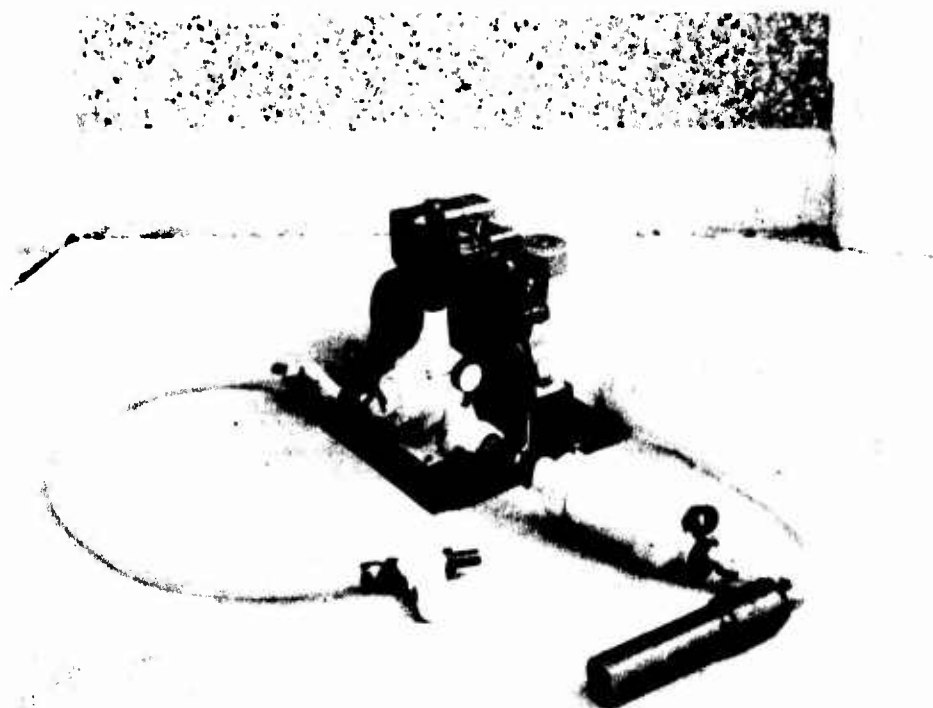


Figure 3.7 Foam generator requiring an auxiliary proportioning tank but no air source.

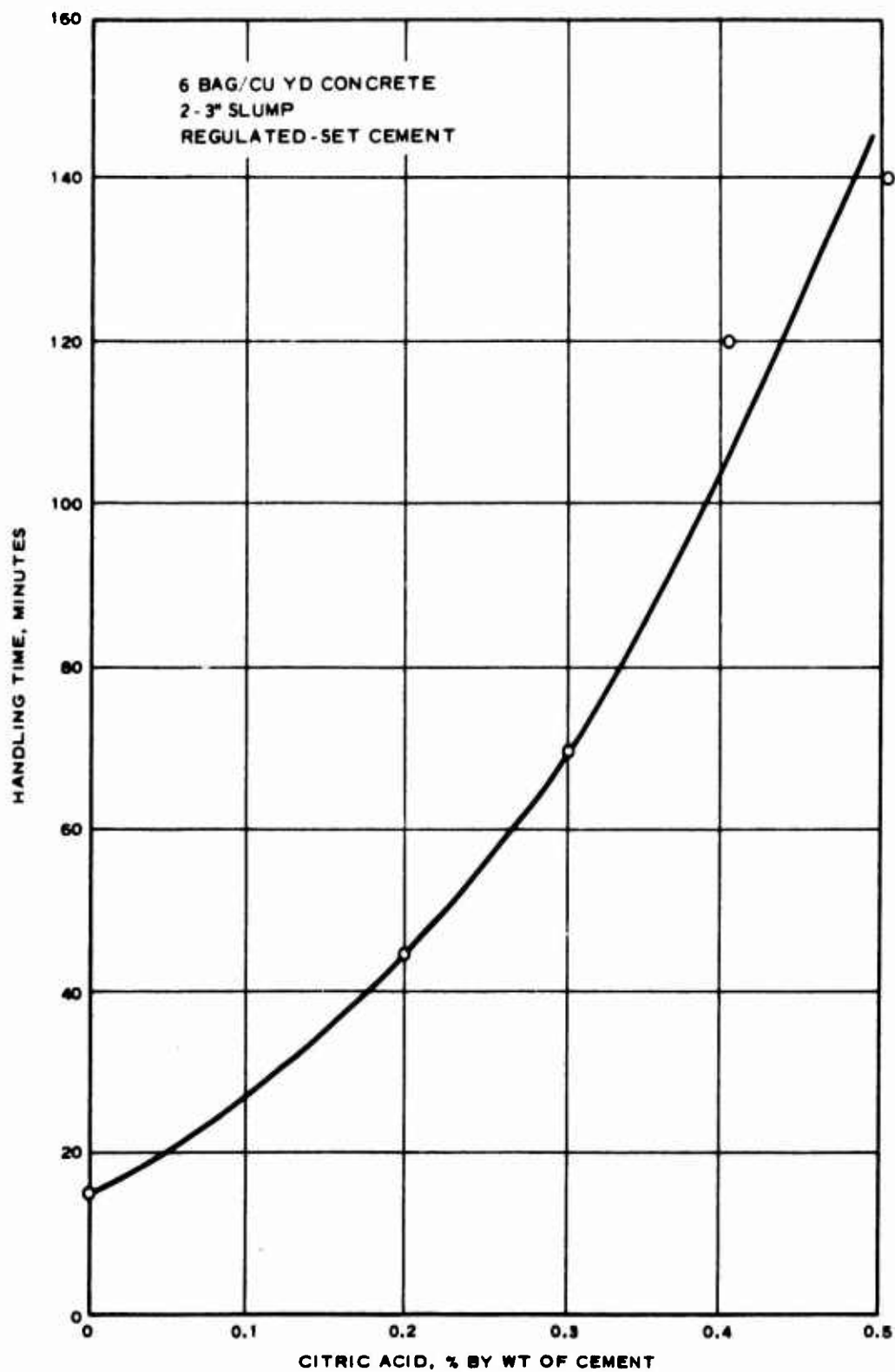


Figure 3.8 Effect of citric acid on handling time of concrete (Reference 17).

FOAM VOLUME CORRECTION FACTORS			
FOAM DENSITY, LB/CU FT	FOAM CORRECTION FACTOR	FOAM DENSITY, LB/CU FT	FOAM CORRECTION FACTOR
4.0	1.000	3.0	0.983
3.8	0.995	2.9	0.981
3.6	0.990	2.7	0.978
3.4	0.985	2.5	0.975
3.2	0.980	2.3	0.972
3.0	0.975	2.1	0.969
2.8	0.970	1.9	0.966
2.6	0.965	1.7	0.963
2.4	0.960	1.5	0.960
2.2	0.955	1.3	0.957
2.0	0.950	1.1	0.954
1.8	0.945	0.9	0.951
1.6	0.940	0.7	0.948
1.4	0.935	0.5	0.945
1.2	0.930	0.3	0.942
1.0	0.925	0.1	0.939

TOTAL WEIGHT OF CONCRETE PER CUBIC YARD					
DENSITY OF CONCRETE, LB/CU FT	TOTAL WEIGHT OF CONCRETE, LB/CU YD	DENSITY OF CONCRETE, LB/CU FT	TOTAL WEIGHT OF CONCRETE, LB/CU YD	DENSITY OF CONCRETE, LB/CU FT	TOTAL WEIGHT OF CONCRETE, LB/CU YD
10	810	40	1080	50	1350
11	891	41	1107	51	1377
12	972	42	1134	52	1404
13	1053	43	1161	53	1431
14	1134	44	1188	54	1458
15	1215	45	1215	55	1485
16	1296	46	1242	56	1512
17	1377	47	1269	57	1539
18	1458	48	1296	58	1566
19	1539	49	1323	59	1593
20	1620	50	1350	60	1620

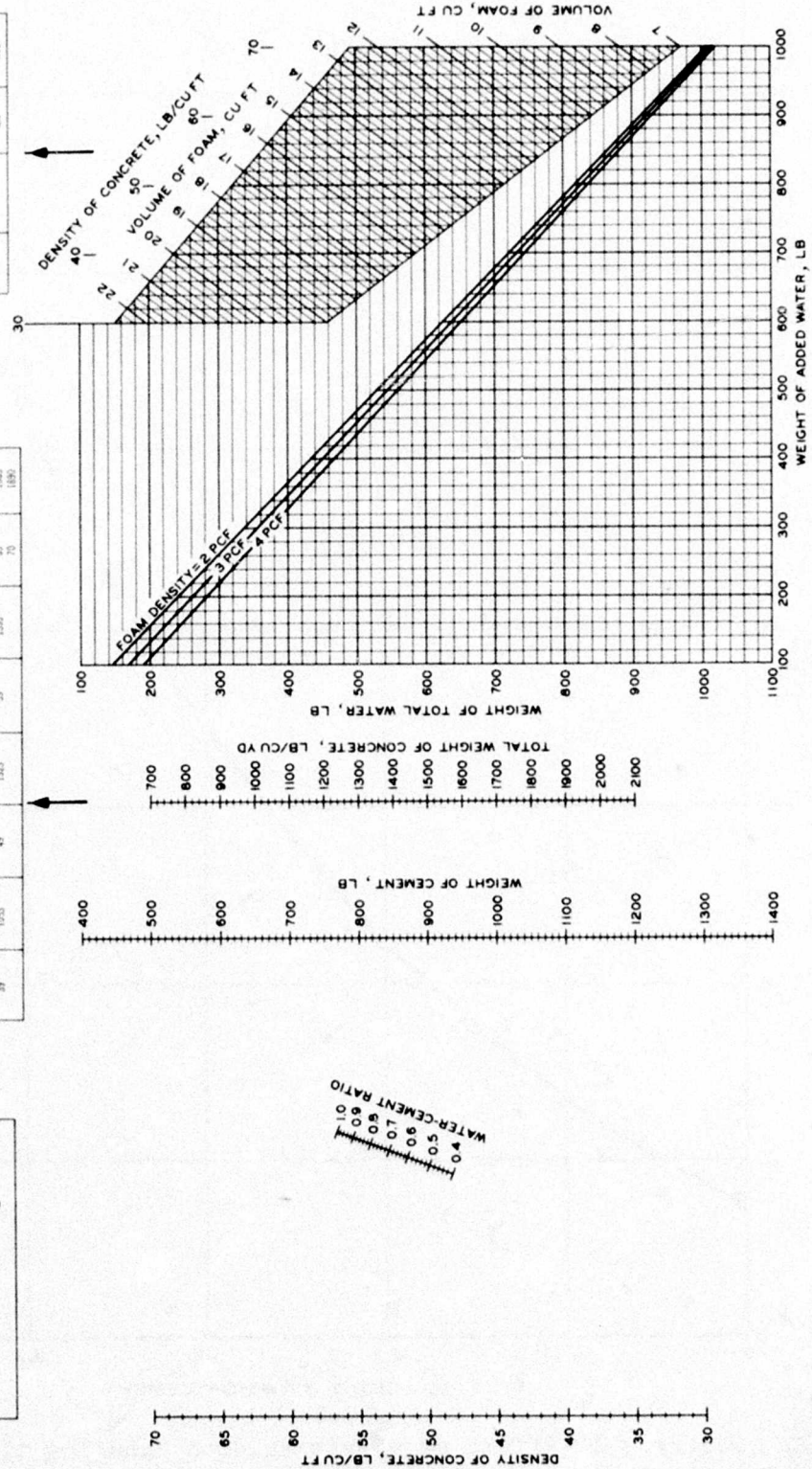
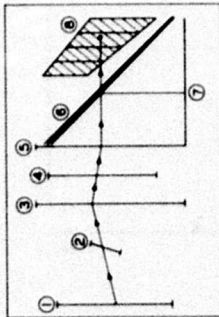


Figure 3.9 Nomograph for proportioning neat cellular concrete.

CHAPTER 4

MATERIALS AND EQUIPMENT FOR FIELD IMPLEMENTATION

4.1 WATER SUPPLY

The exact amount of water required at the crater is difficult to determine and will depend on the mixture proportioning and the amount used for cleanup and washing. To get an indication of how much will be required, however, assume that the wearing or surface cap will have a water/cement ratio of 0.55 (by weight) and a cement content of 800 lb/yd³. This mixture then requires 440 pounds of water or 52.80 gal/yd³ of concrete. From Figure 2.3, the Zone 3 repair would then use:

$$131 \text{ yd}^3 \times 52.80 \text{ gal/yd}^3 = 6917 \text{ gallons}$$

From Section 3.8.1, the sand and air contents are the only differences between Zones 2 and 3; hence, for the Zone 2 repair:

$$205 \text{ yd}^3 \times 52.80 \text{ gal/yd}^3 = 10,824 \text{ gallons}$$

In Zone 1, however, the sand is left out and the air content is increased. Assuming a cellular concrete density of 50 pcf, the cement and water contents increase to 871 and 479 lb/yd³, respectively, which is 57.49 gal/yd³. If half of the material in Zone 1 is debris and the other half cellular concrete, the volume of water required for Zone 3 would be:

$$(137 \text{ yd}^3 : 2) \times 57.49 \text{ gal/yd}^3 = 3938 \text{ gallons}$$

The total water required for the concreting operation alone would be:

Zone 1	3,938 gallons
Zone 2	10,824 gallons
Zone 3	6,917 gallons
Total	21,679 gallons

Assuming an additional 25 percent (approximately) water would be required for cleanup and contingencies, then approximately 27,000 gallons of water is needed for the repair of one crater.

This water can come from fixed impoundments, fixed water delivery systems (pipes or conduits), or mobile delivery systems such as tank trucks.

In planning for water availability, it should be kept in mind that when the airfield is attacked, damage will probably not be confined solely to runways. Fixed delivery systems, including the water towers which develop their operating pressures, may also be damaged or destroyed. Fire-fighting operations may also reduce water pressure levels so that the desired flow rates cannot be achieved at the site of runway repair.

Mobile delivery systems, such as tank trucks, have greater flexibility than a fixed delivery system and could service batching operations at any location. They are limited by their water capacity and their mobility off of paved or prepared surfaces. For standard 1500-gallon tank trucks, which can operate off-road, sufficient trucks to make 18 deliveries to the site must be available for a 27,000-gallon requirement. The actual number will depend on unloading, fill-up, and turnaround times for the trucks.

Impoundments adjacent to runways are the best source of water for the operation. They are relatively immune to a bomb attack and can hold sufficient amounts of water of suitable quality for the repair. The impoundments can be open lakes or holding ponds, which can be integrated into base operations to be aesthetically pleasing and multi-purpose, or they can be reservoirs buried next to runways. If buried, they could be permanent structures made of metal or concrete or temporary structures such as large rubberized bags. In all cases, they should be compartmentalized to reduce their vulnerability to leaking if damaged by a penetrating projectile. If it is not possible to place such impoundments immediately adjacent to the runways, they could be located some distance away and be connected to collecting sumps adjacent to the runways by gravity flowing, open, lined ditches or

large-diameter buried pipe. Release of water, through gates or valves, from the impoundment would fill the sumps and thus provide the necessary water which could be drawn from the sump by pumps and delivered to the batching equipment. The ditches and pipe could also be used for storm-water drainage year-round.

4.2 STORAGE OF REGULATED-SET CEMENT

Throughout the conveying and storing of cement for bomb-damage repair, the cement should be exposed to air as little as practicable because moisture in the air causes partial hydration of the cement. It then becomes lumpy and difficult to work with and can produce low strengths in concrete made with it. Regulated-set cement, although a relatively new product, has been stored for as long as 3 years in air- and watertight silos without detrimental effects as was the cement used in the Tyndall Air Force Base tests described in Section 5.2.

Cement can be delivered in either bags or bulk. Bulk delivery is more desirable because of the large quantities involved. The assumed crater repair used to determine water quantities in Section 4.1 would require approximately 59,664, 164,000, and 104,800 pounds of cement for Zones 1, 2, and 3, respectively, a total of 328,464 pounds. Adding a 10 percent contingency to this, approximately 361,310 pounds (181 tons) would be needed for each crater. This translates roughly into approximately 4000 ft³ of storage space required based on 90 pcf of loose volume density for regulated-set cement.

Cement can be stored in any air- or watertight container. Regulated-set cement has been stored in permanent in-place silos, paper bags, fiber and steel drums, rubberized bags, and mobile bulk tanks. Stationary or semipermanent silos similar to those shown in Figure 4.1 could be fabricated of metal or concrete on virtually any air base. The bulk storage silo on the right of Figure 4.1 has a storage capacity of approximately 177 tons of regulated-set cement. Silos could be located near or removed from runways. Bulk shipment would be required to fill the individual silos. Positive features of silos include:

1. Air- and watertight construction.

2. Adequate capacities.

3. Variety of emptying methods could be employed, i.e., mechanical screws, compressed air, gravity plus vibrators, etc.

Disadvantages are:

1. Highly visible and vulnerable during attack.

2. Because of their size silos near runways may interfere with air traffic.

3. Transporting the cement from the silo to the place of use will be a problem if equipment is rendered inoperable. Equipment as simple as dump trucks could be used, however.

For long-time storage, paper bags are not desirable from two standpoints: The bags only give minimal protection against moisture intrusion even under covered storage, and approximately 4000 bags of cement would have to be handled individually during the repair. Fiber drums, usually cylindrical and of the 40-gallon size, provide better protection, but each drum, if full, would weigh in excess of 450 pounds, thus requiring mechanical handling (forklift, end loader, etc.) which would be difficult since the container is made of a crushable fiber material. Approximately 750 drums would have to be handled for the repair. Cylindrical steel drums, 55-gallon capacity, 16-gage metal with lids, are ideal for cement storage, but as in the case of fiber drums, mechanical handling is necessary as each full drum would weigh in excess of 600 pounds. Approximately 575 drums would be required for the repair. Whenever drums of either type would be used, they would not be emptied directly into the batching equipment but into end loaders or dump trucks which would fill feed hoppers on the batching equipment. Drums can be strategically deployed around airfields with reduced vulnerability during attack.

Rubberized bags (Figure 4.2) are ideally suited for both storage and handling of bulk cement. The bags are usually made of neoprene-impregnated tire cord and are available in a variety of sizes and volumes ranging from 50 to 300 ft³. These bags provide a weatherproof storage facility on location without warehousing. Containers, when empty, may be shipped to a refilling point, filled with cement by

gravity or air pressure, and transported "as is" to another location with no special handling involved. Emptying is accomplished the same way as filling, i.e., gravity or air pressure. The bag shown in Figure 4.2 is more suited for storage and transportation than for rapid unloading. Bags have been made with tapered bottoms which allow extremely fast discharge of the cement. One type of rubberized bag currently available is a 120-ft³ bag which would hold approximately 5 tons of regulated-set cement. The manufacturer claims that the emptying time for this bag is 3 to 6 minutes. Approximately 34 to 36 of these bags would be required for a crater repair.

Mobile bulk storage of cement requires maintaining a large inventory of equipment which may never be used. Figures 4.3, 4.4, and 4.5 show three types of mobile storage tanks. Figure 4.3 shows two each with a capacity of 900 ft³ (approximately 40 tons) of regulated-set cement. These units are emptied with a screw mechanism which is powered by a self-contained power supply. Figure 4.4 is a 500-ft³ (22-ton) pneumatic bulk truck with self-contained power source and rear surcharger. Figure 4.5 is a 750-ft³ (33-ton) field storage unit with self-contained power source and rear surcharger. Standard tractors can be used to transport the unit to the batching site. This system of storage has the advantage of rapidly moving large volumes of cement to a location on very short notice. Disadvantages include the vulnerability of such units during attack and the high initial equipment cost to provide sufficient cement storage (4000 ft³) for each crater to be repaired.

Whatever storage system is used, three criteria must be satisfied:

1. The storage facility must be air- and watertight.
2. In all bulk storage containers, provisions must be made for alternative manual methods of removing the cement from the container, if electric or pneumatic mechanisms or devices fail.
3. Periodic sampling of all stored cement for quality evaluation is necessary to insure a state of readiness. Periodic turnover of stored cement by using it in base concrete work would be desirable.

4.3 FOAMING AGENT

The amount of foaming agent concentrate required per crater repair

will depend on the dilution rate of the particular foaming agent used, the expansion level of the foam, the amount of foam required per cubic yard of cellular concrete, and the amount of cellular concrete placed. The dilution rates of most foaming agents vary from 2 to 8 percent by volume of water, with a cubic foot of foaming solution producing from approximately 20 to 30 ft³ of foam. This gives a foam concentrate requirement varying from 0.007 ft³/ft³ of foam at best to 0.004 ft³/ft³ of foam at worst.

The amount of foam per cubic yard of cellular concrete is dictated by the concrete density, the foam density, and the proportions of all the other ingredients in the mixture (see Equations 3.1 and 3.2). As these factors may vary from repair to repair, it is difficult to obtain an exact determination of foam volume requirements. As an example, however, the quantities determined in Section 3.8.1 for Zones 1 and 2 repairs can be used to get an idea of concentrate quantities involved. Zones 1 and 2 required 15.4 and 7.0 ft³ of foam per cubic yard of cellular concrete. Using the same concrete volumes for Zones 1 and 2 as in the water quantity determinations of Section 4.1, the following foam quantities would be required:

$$\text{Zone 1: } (137 \text{ yd}^3 : 2) \times 15.4 \text{ ft}^3/\text{yd}^3 = 1055 \text{ ft}^3$$

$$\text{Zone 2: } 205 \text{ yd}^3 \times 7.0 \text{ ft}^3/\text{yd}^3 = 1435 \text{ ft}^3$$

$$\text{Total foam required: } 2490 \text{ ft}^3$$

For the worst case of dilution and expansion, the amount of foaming agent required would be $2490 \text{ ft}^3 \times 0.004 \text{ ft}^3/\text{ft}^3 = 9.96 \text{ ft}^3$. The foaming agent usually comes in 55-gallon drums having a capacity of 7.35 ft³. To ensure having an adequate supply on hand, it would then be desirable to have two 55-gallon drums of foaming agent concentrate available for each crater repair.

4.4 RETARDERS

The amount of retarder used will depend on the type of retarder used, the amount of retardation desired, and the particular cement to be retarded. Citric acid is the preferred retarder for regulated-set cement, but other types may also be acceptable. The citric acid used

should be a standard industrial grade in either granular or powder form. It is usually available in plastic-lined paper bags that can be sized for ease of handling or batching. The best approach for use in the field is to prepare a concentrated solution of the citric acid and water and use it in the batching operation. The citric acid in its granular or powder form is extremely soluble and the material goes into solution with simple stirring. Since the solution concentration is known, it can be metered into the cement slurry in the proper proportions to give the effect desired.

4.5 SAND

Sand has been recommended for use in the concretes of Zones 2 and 3 but the possibility of substituting bank-run sand and gravel exists providing the aggregate size does not exceed 3/8 inch. The sand can be stockpiled adjacent to the runways or located elsewhere and trucked into the batching area. Approximately 119 and 187 tons of sand are needed for repair of Zones 2 and 3, respectively, a total of 306 tons per crater. This assumes an 85-pcf cellular concrete density in Zone 2 and a 10 percent contingency for handling and storing losses.

4.6 MIXING AND PLACING EQUIPMENT

4.6.1 Requirements. The maximum rates for concrete placement will occur in Zones 2 and 3 of the crater (Figure 2.3). Zones 2 and 3 will require approximately 205 and 131 yd³ of concrete, respectively, a total 336 yd³. A reasonable placement time for this material should not exceed 2 hours, which would require a placing rate requirement of approximately 170 yd³/hr as a minimum. From practical considerations, which include the physical size of a concrete production unit of this capacity, the technology needed to construct such a unit, and the vulnerability to attack of a single piece of equipment, not less than three units should be used simultaneously to obtain the desired placing rate. This would require a minimum placing rate of 57 yd³/hr for each unit, well within the current state of equipment development for the construction industry.

Each unit should be self-contained and not require supporting equipment for its operation. It should include either a gasoline or diesel engine for power, a water pump for obtaining the necessary water pressures for operation, a mixer, a foam generator, and a pump. As some types of foam generators require a compressed-air source, an air compressor may also be required. The feed mechanisms of the dry materials (sand and cement) do not necessarily have to be a part of the unit, but it would be desirable. The entire unit should be mounted on a single trailer suitable for towing by a jeep or large vehicle.

4.6.2 Power Sources. The size and type of gasoline or diesel engine used should allow it to furnish all the power required for operating the unit for extended periods of time at ambient air temperatures from 0 to 110°F in both sunny and inclement (rain, snow) weather. The fuel tank should be of such capacity to sustain operation of the unit for the complete job so that no possibility of a shutdown exists. Refueling during operation should be considered as a last option. If a unit inadvertently shuts down due to the lack of fuel, the loss of power will also cause the pump to stop operating and, with the very fast hardening characteristics of the cement, the material in the mixer and discharge hose will harden within a few minutes, thus rendering the unit inoperational for the remainder of the job.

The power conversion equipment necessary to accomplish the desired requirements can include manual or automatic shift transmissions, hydraulic pumps and motors, air motors, electric generators and motors, etc., but all should be powered primarily by the engine used.

As the source of water may not be under any head of pressure, a water pump should be installed to provide the required pressure for operation. Piping and valving should be such that wash and cleanup water is available from a faucet on the unit. As there may be a requirement for using a retarder with the cement, a venturi aspirator with appropriate regulating valves and pickup hose should be provided in the main mix waterline to pick up a solution containing the retarder and put it into the mixing water. This is similar in principle to the simple garden hose sprayer.

4.6.3 Mixing Equipment. The mixer should be of such construction and capacity that the slurry produced is free of lumps. The dwell time of the material in the mixer should be between 30 and 90 seconds. The consistency of the mix should be controlled mechanically by setting the ratios of materials carried through the dry material feed mechanisms to the amount of water injected in the tub.

4.6.4 Batching Equipment. The cement and sand should be fed into the mixer, preferably through the top opening, at controlled rates. The feed mechanisms can be either power-driven, such as augers or conveyor belts, or gravity fed, although the latter is not desirable. Augers and belts should have end hoppers for loading purposes. Because of the possibility of inclement weather operations, the feed mechanism should be sealed or covered to prevent water from prematurely wetting the materials. The feed mechanisms ideally should be a part of the unit, but this is not required. For planning the repair operations, the worst materials usage would require the cement and sand to feed into the mixer at rates of 1900 and 4000 lb/min, respectively. To avoid excessively large or expensive equipment, the sand can be fed by one or more feed mechanisms operating simultaneously. Controls should be provided to adjust the feed rates of the mechanisms from maximum to zero flow.

At worst, the mix water requirements would be between 220 and 230 gal/min. Most operations would involve less than 100 gal/min, however. The mix water would best be dispersed in the mixer by some type of spraying device, such as a spray ring around the top of the mixer. This process will help avoid cement lumping in the mixer. An adjustable metering system should be provided for water control.

Preformed foam generators are available in a wide variety of sizes and operating modes, but the end product is essentially the same, with the foam varying mostly in density and rate of discharge. As mentioned above, the placing rate for three units operating simultaneously in the upper regions of the crater would be approximately $60 \text{ yd}^3/\text{hr}$ per unit. For the density range anticipated for sanded cellular concretes in these locations ($>70 \text{ pcf}$), foam volume requirements would vary from 12 to $14 \text{ ft}^3/\text{yd}$ of concrete at 70 pcf to 0 for the capping material. At

60 yd³, the foam generator output requirements then should be 14 ft³/min. The preformed foam can be introduced into the batching system at any point where it can be thoroughly blended with the slurry or mortar. The foam could be put into the mixer directly or, depending on the pump used, into the pump directly. In the latter case, a backflow valve should be provided at the point of foam input to prevent slurry or mortar from flowing into the foam generator when it is not in use. A constant rate of discharge for the generator is acceptable as the amounts of other materials can be readily adjusted to the foam volume to provide the desired concrete density.

Some foam generators automatically proportion the foaming agent concentrate and water, while others require the preblending of the concentrate and water. In the latter case, provisions must be made for blending and holding tanks for the solution. These do not necessarily have to be part of the mobile unit and can simply be clean 55-gallon drums with a solution pickup provided from the unit to the drums. In no case should drums be used that have not been steam-cleaned since residues of certain materials, especially petroleum products, render the foaming agent ineffective.

4.6.5 Pumping Equipment. The pump for the concrete should be a positive-displacement type (rotor-stator) or squeeze type. Single- and double-action piston pumps will not pump high air content cellular concretes. The pump can be driven hydraulically or by air, its speed should be variable with appropriate controls provided, and it should have a capacity sufficient to pump 80 yd³/hr of a coarse sand mortar for distances up to 500 feet with no vertical lifts. A pump pressure indicator would be desirable at the discharge end of the pump as a precautionary measure to indicate when substantial buildups are occurring in the placing lines or hoses.

4.6.6 Placing Lines. The placing lines or hoses for the concrete should be sized to keep the material flowing through them at a fairly fast rate when the pump is operating to keep the cement from building up in the lines and plugging them. Lines of 500-foot length and 4, 5, and 6 inches in diameter, when flowing full, would contain approximately

1.6, 2.5, and 3.6 yd³ of material, respectively. At a placing rate of 60 yd³/hr, the material would be in the lines approximately 96, 150, and 216 seconds. If the material had a mixing (dwell) time of 90 seconds, material in the 6-inch-diameter line would have had its cement in contact with water for more than 5 minutes, and this, on hot days if the cement is not retarded, is not desirable as plugging will probably occur. Placing lines of 4- or 5- inch diameter are probably more desirable for this type of application. The type of material used for the lines or hoses can be varied, but from practical considerations, the material should be relatively inexpensive, lightweight, flexible, easy to assemble, have a smooth interior wall, and have sufficient strength to resist bursting under pumping pressures. Polyvinyl chloride (PVC) pipe satisfies these requirements. It is easily joined by using PVC cement, which hardens in a few seconds, and sized sleeves for the diameter pipe being used. PVC pipe can be cut with a handsaw and is easy to clean. Grades of PVC pipe are available to withstand the pump pressures anticipated for the equipment described above. The pipe should be white to prevent the absorption of excessive amounts of solar energy during the pumping operation. Dual placing lines should be established for each placing unit in case problems develop in one line; the other can then be rapidly hooked up and used. The PVC pipe should be connected to the pump with a section of flexible rubber hose. A flexible sleeve or hose piece should be provided at the discharge end of the line for ease of movement in the crater.

4.6.7 Specifications. A sample specification for a self-contained, portable cellular (foam) concrete mixer and placing unit is contained in Appendix A. It can be easily modified to conform with more specific requirements of the expected use of the unit or the more detailed requirements in the previous paragraphs.

4.6.8 Availability. Units similar to those described above and in Appendix A are presently manufactured for use in the foamed gypsum and cellular concrete floor fill and roof deck industry. The designed production rates of these existing units are dictated by the volumes of material usually placed in floors and decks and the manpower necessary

to handle, place, and finish the material and, as such, may be less than those needed for bomb-damage repair. The units can be upgraded to satisfy bomb-damage repair requirements, however. Figures 4.6 and 5.36 show two such units. Figure 4.6 shows a cellular concrete production unit with a built-in foam-generating system; a gypsum pumper that must have a foam-generating system added is shown in Figure 5.36.



Figure 4.1 Cement storage silos.



Figure 4.2 Rubberized storage bag for cement.

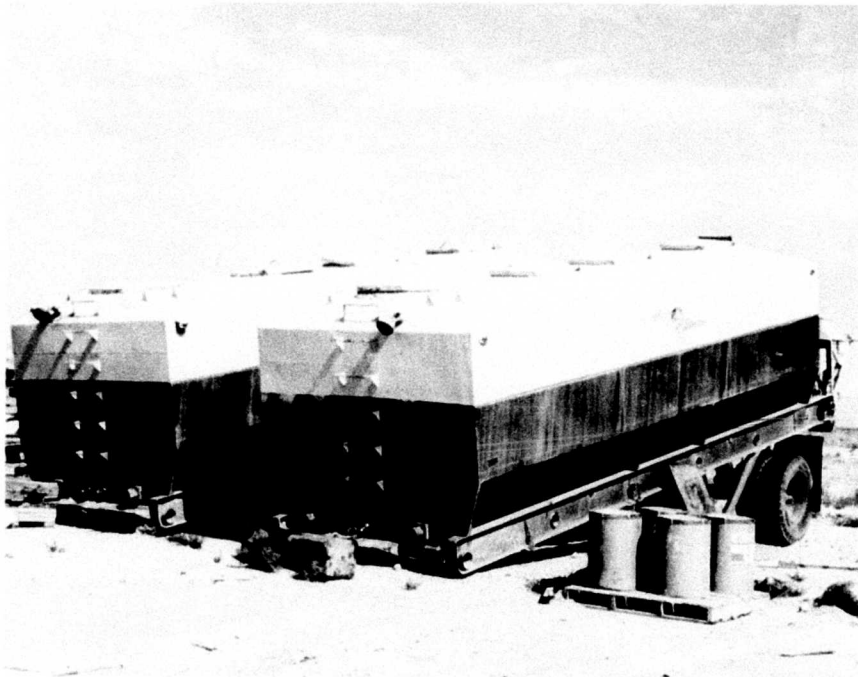


Figure 4.3 900-ft³ mobile storage tanks.



Figure 4.4 500-ft³ pneumatic bulk tanks.

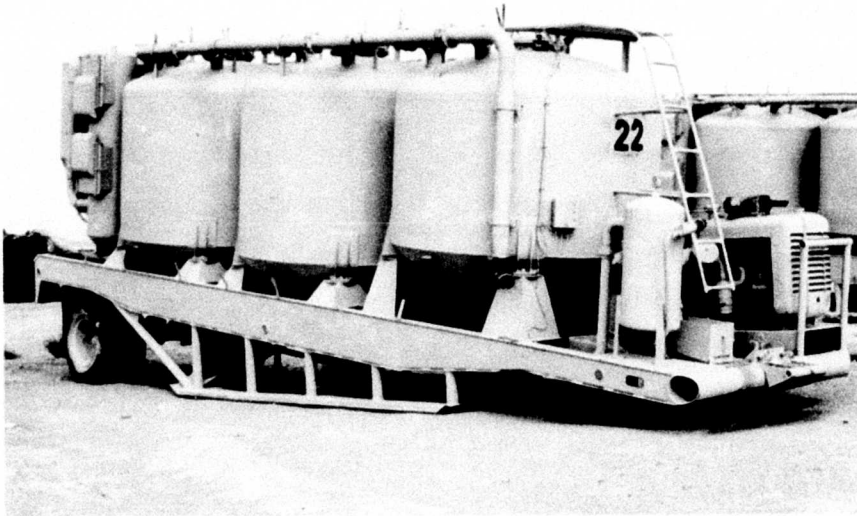


Figure 4.5 750-ft³ field storage tank.

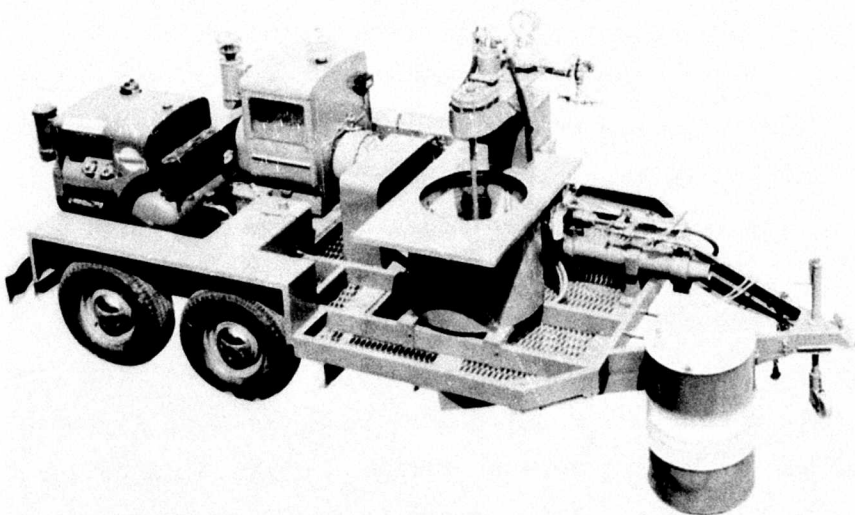


Figure 4.6 Self-contained cellular concrete production unit.

CHAPTER 5

FIELD TRIALS

5.1 WES TESTS

5.1.1 Small Simulated Crater Repair. The first attempt to use cellular concrete made with a regulated-set cement for filling a small simulated crater was conducted at WES. The simulated crater was a hole remaining from a previous study and is shown in cross section in Figure 5.1. As shown, the crater volume was approximately 4 yd³. Figure 5.2 is an overall view of the crater opening. The rock debris in the bottom of the crater was placed to simulate some debris that might remain in an actual crater. Eleven thermocouples were placed at various locations throughout the crater as a means of observing the temperature buildup caused by the hydration of the cement. Another thermocouple was used to measure ambient air temperatures.

The cellular concrete fabrication equipment included a 4.5-ft³ mortar mixer, a foam-generating unit, air compressor, and 110-220-volt electrical generator. The necessary water was obtained from a nearby fire hydrant. The air compressor and electrical generator were needed to operate the foam-generating unit. The volume of the mortar mixer was inadequate for the job at hand, but was the only size available.

The cellular concrete consisted of regulated-set cement, water, and air. According to the batching sequence, the water was placed in the mixer first. The cement was then added and mixed for approximately 1 minute. The air, in the form of a preformed foam, was then introduced into the slurry and blended for approximately 2 minutes. The concrete was then ready to be dumped into the crater. The cellular concrete was to be made with a constant water/cement ratio of 0.55 (by weight). The initial goal was to make concrete at five different densities corresponding to 35, 50, 65, 85, and 110 pcf and to fill the crater from the bottom up with concrete of increasing density. The 110-pcf concrete would have no air or sand added to it; this was to be the capping material. The cement and water were weighed for each batch. The amount of foam added

to each batch was determined from a discharge rate calibration for the foam-generating equipment and was controlled by an automatic timing device.

Twenty-seven batches of concrete were made. A breakdown of the batching and concrete densities and volumes is as follows:

<u>Design Density pcf</u>	<u>Freshly Mixed Density pcf</u>	<u>No. of Batches</u>	<u>Approximate Volume ft³</u>
35	25.6	6	24
50	46.8	8	32
65	63.0	6	24
85	83.8	4	16
110	110.6	3	12
Total		27	108 ft ³ (4 yd ³)

The average time between discharging each batch from the mixer was approximately 4-1/2 minutes. The mixer had to be cleaned after batching each of the first three densities (35, 50, and 65 pcf) because of cement buildup on the mixer blades. It, of course, was also cleaned upon completion of the job. All placing was complete in 3 hours. A total of 4300 pounds of regulated-set cement was used.

Figure 5.3 shows the general appearance and level of the cellular concrete shortly after the beginning of the 50-pcf-density batching. The protruding rod was used to position some of the thermocouples in the center of the section. Figure 5.4 shows the general appearance and level of the cellular concrete immediately after placement of the last batch of 65-pcf-density concrete. The roughness of the surface was caused by moving the material with a shovel to keep it from piling up. Figure 5.5 is the same surface in Figure 5.4, 10 minutes later. A 150-pound man could stand and walk on the surface without leaving an indentation; this is indicative of a CBR greater than 10. Figure 5.6 shows the placement of the 85-pcf-density concrete. Despite its fluid appearance, the mixture did not flow very well. Figure 5.7 shows the surface after placement; it was somewhat irregular and rough. The continuous-recording equipment for thermocouple output can be seen in the large drill bit in the upper right of the figure.

Because of the irregular features of the final cast surface, an attempt was made the following day to level the surface by placing a more flowable, neat, regulated-set cement slurry over the original placement. The neat slurry had a water/cement ratio of 0.70 (by weight) and a density of 102.7 pcf. Approximately 4 ft^3 of slurry was placed, and although it did improve the appearance of the surface, it did not make it perfectly smooth. Upon hardening, the new cap cracked badly. Figure 5.8 shows the surface approximately 30 minutes after placement of the slurry.

The thermocouples indicated that the maximum temperatures developed during placement were 208°F and occurred approximately 3-1/2 hours after the start of the operation. The maximum temperature-time history for the concrete is shown in Figure 5.9. The ambient temperature at that time was 78°F . This level of temperature development was expected. In order to check the effect of this large temperature increase on the volume stability (thermal bulge) of the placement, a number of measurements were made on the exposed top surface. Prior to the start of the concreting operation, an engineer's level had been set up adjacent to the crater and a reference benchmark was established. Approximately 1 hour after placement of the 110-pcf-density concrete, a number of rod readings were made on the surface of the placement. A steel tape having 1/100-inch markings had been fastened to the leveling rod so that small changes in the surface level could be observed with the level. Subsequent readings were made throughout the day and the following morning at the same points on the surface that the original readings were taken. An average increase (17 readings) in the surface elevation of 0.02 inch was observed 1 hour after the initial readings were taken. At 2 hours, the increase was only 0.01 inch. At 3 hours, the surface elevation appeared to have subsided slightly to a point 0.06 inch below the original surface; it remained at this level throughout the night and the following morning. Once the additional capping was added, no more readings were possible. This slight decrease in elevation may be attributed to the loss of heat and localized cooling near the surface of the concrete which would cause some thermal contraction.

During placement of each density of concrete, three 6- by 12-inch cylinders were cast for strength determination purposes. The concrete for each cylinder set representing a particular density was taken from the third batch made at that density. All cylinders were cast in cardboard molds. The freshly mixed densities shown above were obtained by weighing each cylinder set immediately after casting and then calculating the density. Ideally, the strengths of these cylinders should have been determined while placement was going on or shortly after casting, but this was not possible due a shortage of personnel. The specimens were tested at 28 days, however, to obtain some indication of strength. All specimens were removed from their cardboard molds at 24 hours age and were subsequently bag-cured at 73°F until tested. The 28-day strengths were as follows:

<u>Density</u> <u>pcf</u>	<u>28-Day Compressive</u> <u>Strength, psi</u>
25.6	a
46.8	310
63.0	810
83.8	1930
110.6	4220

a Cylinders were damaged during removal of the molds and were not tested.

In summary, the first attempt to fill a crater with cellular concrete made with regulated-set concrete was successful, and a number of areas for further consideration were realized. The most obvious was that the actual mixing equipment used was not suitable for large-scale work. The cellular concrete made with regulated-set cement did not flow as readily as when made with normal portland cement. Some provisions would have to be made to eliminate cracking in the capping material. The volume stability of the mass did not seem a problem, even with large temperature increases. Strength development and rate of hardening appeared adequate.

5.1.2 One-Sixth Size Crater Repairs. The filling of two one-sixth volume size craters was also done at WES. These craters were not created by explosives but were excavated in a loess soil with a backhoe to the

approximate dimensions of 7 feet deep, 25 feet in diameter at the top, and 10 feet in diameter at the bottom; this provided a volume of approximately 65 yd³ to be filled. The excavated soil was piled around the edge of the crater to simulate thrown-out debris.

5.1.2.1 PVC Pipe Module Test. The first crater was filled using a scheme developed at Texas Tech University (Reference 25). This scheme involved using prefabricated modules of PVC pipe as structural fillers for the crater. These modules were to be cemented in place in the crater using regulated-set cement cellular concrete and covered with a regulated-set cement structural cap. Figure 5.10 shows the proposed crater filling scheme. This operation was designed to evaluate the filling procedure with no attempt being made to maximize the percentage of crater volume filled by modules. Four modules were used, each constructed with 10-inch-diameter PVC pipes of 0.20-inch wall thicknesses. The bottom module (Figure 5.10) was 3 feet high; the top layer modules were 2 feet high. The modules were constructed at the Civil Engineering Laboratory, Texas Tech University, using the procedures described in Reference 25.

The batching unit used is shown in Figure 5.11. It is basically a gypsum cement batching and pumping unit similar in operating principle to the unit described in Section 4.3. It was modified by the introduction of a foam generating unit (Figure 3.7) which was hooked up to the bottom of the pump on the batching unit. This unit provided the foam during the cellular concrete portion of the operation. The batching and pumping unit was further modified by the addition of a large cement hopper over the smaller hopper that was an integral portion of the unit. This larger hopper would provide a constant supply of cement to the system as the smaller hopper on the unit could not be kept full enough to keep up with pumping demands when delays in cement unloading occurred.

The original scheme for cement handling used rubberized storage bags as described in Section 4.2. These bags (Figure 5.12) were handled by a mobile crane. These were storage bags, not designed for rapid discharge. Their rate of emptying could not keep up with the cement demands of the batching and pumping unit, even with the use of the

larger supply hopper. This approach was abandoned and replaced with a field storage tank delivery system (Figure 5.13). This unit consisted of three storage tanks and a surcharge tank. Each storage tank was approximately 400 ft³ in capacity and all three tanks were hooked together in series with the cement being moved pneumatically between them as needed. The tanks were filled initially with a conveyor (Figure 5.13). The tanks could be refilled while the operation was in progress. The surcharge tank holds some cement for ready gravity-discharge and was positioned over the small hopper on the batching and pumping unit. With one man monitoring it, the hopper could be kept full at all times, thus providing an uninterrupted flow of cement for the batching operation.

The regulated-set cement was moved from the small hopper to the mixer by means of an auger (screw) conveyor that was part of the batching and pumping unit. The rate of cement feed was regulated to that of the water delivery so that a slurry with a water/cement ratio of 0.55 was produced in the mixer. The slurry was pumped from the mixer at different speeds, depending on whether the cellular concrete or the neat capping material was being placed. When the cellular concrete was being produced, the foam generator was operated at a discharge rate of 10-11 ft³ of foam per minute; approximately 95 percent of this foam was air. The pump speed was varied to combine the slurry, which had a theoretical density of 109.6 pcf, with the preformed foam with an approximate density of 3.2 pcf, in proportions that would produce the desired density of the cellular concrete. At maximum pump speeds, a placing rate for this unit of approximately 45 yd³/hr for neat cement slurries could be achieved. This rate was slower for the cellular concrete placing because of the slower fixed rate of discharge of the foam generator.

The concrete was placed through a 3-inch-diameter PVC pipe. The pipe came in 20-foot sections and was joined by PVC-glued sleeves. A 10-foot flexible rubber hose connected the pipe to the pump. The overall pipe length was 180 feet with a 20-foot flexible hose on the discharge end to facilitate movement in the crater. Two such lines were

established in case a problem developed in the primary line.

The prefabricated modules were brought to the repair site on a flatbed truck and unloaded by means of a 15-ton-capacity mobile crane (Figure 5.14). Holes had been drilled in the outside pipes of the modules so that lifting lugs on the crane cables could be easily hooked and unhooked. Prior to placement of the first module, some neat regulated-set cement slurry was pumped into the bottom of the crater to act as a leveling and seating course for the first module. The 3-foot-high module was then lowered onto the crater bottom (Figure 5.15), at which time the cellular concrete placement was then begun. Plans had been made to continually push the soil piled around the crater lip into the crater as the cellular concrete placement continued but this practice was discontinued shortly after it was begun. In pushing the soil over the edge with a bulldozer, the soil was not entering into the cellular concrete but instead was forming a loose, unconsolidated perimeter around the crater which was being covered over by the concrete. In practice, this edge would provide a zone of weakness when the crater was loaded by an aircraft.

The end of the discharge line was shifted in the crater by two men using ropes (Figure 5.16). The cellular concrete would only flow 5 or 6 feet so the line had to be continually shifted. As the cellular concrete neared the top of the bottom module, the other three modules were lowered into the crater and positioned on the bottom module (Figure 5.17). These modules actually penetrated a few inches of the rapidly stiffening cellular concrete, thereby effectively cutting off the flow of the cellular concrete up into the top layer of pipes. The top of the pipes were covered with a large nylon sheet (Figure 5.18) which was taped to the sides of the pipes. This sheet covered the lifting holes and the top opening in the pipes (Figure 5.19), thereby sealing the pipes from the intrusion of the concrete. The cellular concrete was placed up to the top of the modules (Figure 5.20), the neat cement cap then being placed over the entire section. Note in Figure 5.20 that the regulated-set cement cellular concrete could sustain foot traffic within a few minutes after placement.

The capping operation highlighted a problem area related to getting a smooth surface on the repair. It had been assumed that the neat cement slurry would flow easily and be self-leveling. Although it flowed some, it would not flow over the entire area before becoming too viscous and thus it produced a layered material with a bumpy, wavy surface. Screeding was impossible without set guides. The problem could be solved by providing smaller sections for placement by means of joint boards which could also double as screed guides, and by slightly retarding the slurry to provide more working time before it stiffened.

The air temperatures at the start and finish of the operation were 57 and 60°F, respectively. The average slurry temperature during batching was 87°F. No retardation was added to the mixtures. The average cellular concrete density was 34.6 pcf while the capping material had an average density of 95.0 pcf. The capping material density was 14.6 pcf less than the theoretical, no-air density for that mixture. A check of air contents indicated that the capping slurry, after pumping, had an air content of 4 percent. At this air content, the water/cement ratio of the slurry would have to have been approximately 0.94 (by weight) to produce the density of slurry actually obtained. A check of the batching system revealed a problem in the rate of cement feed calibration which was causing less cement to be delivered to the slurry than needed. With a constant water flow rate, the subsequent water/cement ratio was then substantially higher. This high water content was evident in the strengths of 3- by 6-inch cylinders made from the capping slurry. These had strengths of 285, 350, 400, and 560 psi at ages of 1:20, 2:00, 2:20, and 24:00 hours:minutes after casting, which were well below the desired strengths.

Temperature measurements were conducted during the placing trial using two thermocouples placed, one each, at locations approximately 1-1/2 feet from the top and bottom of the crater. The resulting temperatures were as follows:

Elapsed Time hr:min	Temperature, °F	
	Bottom	Top
0:20	95	--
0:30	113	--
0:40	118	--
0:50	121	81
1:00	128	100
1:10	129	116
1:20	131	122
1:30	131	125
2:20	138	134
3:20	140	142
19:50	190	190

No load tests were conducted on the crater repair although a front-end loader was driven onto the repair 15 minutes after it was completed in an attempt to scrape the surface level. The scraping was not successful and the loader cracked the edge of the pavement which overlaid the unconsolidated soil pushed into the crater during the repair. Some drying shrinkage cracking was also noted a short time after the repair was completed.

The manpower used in this repair can be broken down as follows:

	<u>Men Required</u>
Module delivery truck	1
Mobile crane	1
Batching & pumping unit	2
Hose manipulation	2
Module placement	2
Dozer operation	1
Repair supervision	<u>1</u>
Total	10

The personnel required for the module delivery and placement (four men) were only needed for the first one-third of the repair time. In situations involving the use of joint boards and screed guides, these personnel could then be set to preparing these items for installation. The actual repair took slightly more than 2 hours using the equipment described above.

5.1.2.2 Cellular Concrete Backfill Test. The second one-sixth volume size crater to be filled is shown in Figure 5.21. Heavy rains had filled the crater with approximately 18 inches of water which had

to be pumped from the crater prior to start of the repair. The same batching equipment and procedures used for the PVC module repair were used in this repair. The length of PVC placing line was 120 feet with a second "backup" line again being provided. The placing lines for both crater repairs can be seen in Figure 5.22.

The entire crater, except for the cap, was filled with cellular concrete. Attempts were again made to place the loose soil in the crater simultaneously with the concrete. An end loader was used in this repair to move the soil out over the concrete and dump it onto the concrete surface (Figures 5.22 and 5.23). This approach was more successful than the pushing operation used in the PVC module repair, but still it was not highly effective. The placement continued (Figure 5.23) with no problems. The cellular concrete was brought to a level approximately 9 inches below the desired finished surface of the repair (Figure 5.24) at which time joint boards in the form of 2- by 8-inch timbers were placed on the cellular concrete surface as shown in Figure 5.25. These boards were roughly leveled using a carpenter's level. In areas where the cellular concrete backfill had become too high, it was easily removed with a shovel. As soon as the boards were set in place, the neat capping slurry was pumped (Figure 5.26) into the quarter segments, one at a time, until the cap was complete. Figure 5.27 shows the completed cap and finished surface 15 minutes after the pumping. One quadrant was not completely filled because the cement supply for the slurry was depleted and not enough slurry could be made. The surface had been roughly screeded and was fairly smooth and level. A portion of the surface containing a few shrinkage cracks is shown in Figure 5.28.

The air temperatures at the start and finish of the operation were 70 and 75°F, respectively. The average slurry temperature during batching was 84°F. No retardation of the mixtures was used. The average cellular concrete density was 37.5 pcf, while the capping material had an average density of 104.7 pcf. This capping slurry density was a significant improvement over that used in the PVC pipe module repair. This slurry also had an average air content of 4 percent after pumping

and probably had a water/cement ratio slightly higher than the 0.55 (by weight) design. The strengths of 2-inch cubes of the capping material were 790, 935, 1120, and 1250 psi at 1, 3, 5, and 24 hours, respectively. The 4- and 7-day strengths were 2900 and 3115 psi, respectively. No concrete temperature measurements or load tests were made for this repair.

The manpower used in this repair was as follows:

	<u>Men Required</u>
Batching & pumping unit	2
Hose manipulation	2
End-loader operation	1
Repair supervision	$\frac{1}{6}$
Total	6

The joint board assembly, its placement, and the screeding of the cap were accomplished by the repair supervisor and one of the hose men.

The shrinkage cracks shown in Figure 5.28 occurred shortly after the concrete had hardened. These cracks were caused primarily by the withdrawal of water from the cement paste due to evaporation. This loss of moisture will cause a change in volume in the hardened paste when it reaches a point at which the free water in the concrete has all been removed and the absorbed water begins to be removed. Further losses then cause further decreases in volume. As the paste attempts to decrease in volume, it is restrained by the adjoining paste, and tensile stresses develop in the paste. When these stresses exceed the tensile strength of the paste, a crack occurs. At the very early ages of the hardened paste, the tensile strength is very low and the paste will crack easily. This problem is usually reduced by moist- or water-curing the hardened paste. When no moist- or water-curing is given to the hardened neat cement paste, problems such as that shown in Figure 5.29 occur. This surface results from a severe case of drying shrinkage together with a slight upheaval of the pavement caused by side-sloughing of the unconsolidated soil on the sides of the crater wall after a 6-inch rainfall. This degree of cracking did not occur until almost 6 weeks after the material was placed. This type of shrinkage cracking has been well documented for many years and was anticipated in the neat

hardened paste surfaces of the two one-sixth size crater repairs. Although not observed by the author, it was reported that a similar cracking problem occurred in tests conducted at Tyndall Air Force Base, Florida (see Section 5.2.4).

Many factors affect the amount of drying shrinkage that occurs in an element containing a hydrating portland cement. These include the unit water content of the concrete, the composition of the cement, the quality and quantity of paste in the concrete, the characteristics and amounts of admixtures used, the proportions of the mixture, the mineral composition of the aggregate, the maximum size of the aggregate, the size and shape of the element, the amount and distribution of reinforcing steel, the curing conditions, the length of the drying period, and the humidity of the surrounding air (Reference 26). One of the most important influences is that exerted by aggregate which restrains the amount of shrinkage that can actually be realized (Reference 27). The ratio of shrinkage of concrete (or mortar), S , to shrinkage of neat paste, S_o , depends on the aggregate content, g , in the concrete (Reference 28) and is expressed as

$$S = S_o(1 - g)^\alpha \quad (5.1)$$

The experimental values of α have been reported to vary between 1.2 and 1.7 (Reference 27). For the neat cement paste cap used in the two one-sixth size crater repairs, the addition of sand to the mixture should have reduced the drying shrinkage according to Equation 5.1 as follows:

Water/Cement Ratio	Sand/Cement Ratio	Drying Shrinkage Reduction, %	
		$\alpha = 1.2$	$\alpha = 1.7$
0.55	0	0	0
	1.0	34.8	45.5
	1.5	44.9	57.0
	2.0	52.4	65.0
	2.5	58.2	71.0
	3.0	62.9	75.4

At sand additions of approximately 3730 lb/yd³ (sand/cement ratio = 2.50),

which is a reasonable addition for the repair purposes, a shrinkage reduction between 58 and 71 percent should be possible.

The cracking in the surfaces of the two one-sixth size craters strongly suggests the need for sand additions to the capping material and also the use of some water-curing, perhaps just by sprinkling or periodic wetting with a hose, immediately after hardening and until the repair is put into use a few hours later. Two small slabs, 6 by 20 feet by 8 inches thick, were also cast (Figure 5.30) to check the effectiveness of both wire mesh and the sanded slurry in reducing the shrinkage cracking. The wire mesh, 6 by 6 by No. 10, was placed 2 inches under the surface of the slab. The sanded slurry had a water/cement ratio of 0.55 and a sand/cement ratio of 2.40. Both slabs were moist-cured by hose sprinkling for 4 hours after casting. They were then allowed to cure under ambient outdoor conditions in Vicksburg, Mississippi, in May and June. After 28 days, the wire-mesh slab had some minor cracking which was uniformly distributed over the slab. The sanded slurry slab had only one visible crack at one corner, suggesting that additions of sand to the mixture were preferable to wire mesh, and that the wire mesh was preferable to no additions at all.

5.2 TYNDALL AIR FORCE BASE TESTS

Field tests were conducted at Tyndall AFB as part of a series of major field tests for the Air Force runway research program. In these tests, every effort was made to simulate actual repair conditions. A runway section was constructed to simulate existing NATO base runways. The runway was unreinforced concrete and overlaid with asphalt. The runway section covered both clay and sand subgrades.

Three major craters (Type 3--standard) and three smaller craters (Type 2--blowout) (Figure 1.3) were planned for repair using regulated-set cement. A description of the proposed repairs follows:

1. Blowout craters.

- (1) Regulated-set cement cap over debris and granular fill, in a sand subgrade.

- (2) Regulated-set cement slurry-fill aggregate composite caused by allowing cement slurry to percolate down through the fill aggregate. The crater will be debris-filled in clay subgrade.
- (3) Regulated-set cement cap over cellular concrete fill in a clay subgrade.

2. Standard craters.

- (1) Regulated-set cement cap over a composite PVC pipe module-cellular concrete fill in a clay subgrade (see Section 5.1.1 and Reference 25).
- (2) Regulated-set cement cap over a debris-filled crater and uniformly graded sand base course in a sand subgrade.
- (3) Regulated-set cement cap over a composite debris-cellular concrete fill, with a cellular concrete base course in clay subgrade. Due to scheduling problems and lack of funding, Tests 2b and 2c were not conducted.

5.2.1 Equipment. Two schemes were used for the cement handling. A large gravity-feed storage hopper (Figure 5.31) was assembled for use in repairing the blowout craters. The storage hopper had three discharge outlets to service each of the feed hoppers on the three batching units. The feed hopper-storage hopper arrangement can be seen in Figures 5.32 and 5.33. The storage hopper was filled by discharging the cement from rubberized storage bags into the top of the hopper as shown in Figure 5.31. These storage bags were not designed for rapid emptying and with the rapid use of cement in the slurry batching, the hopper was periodically emptied as the bag loading could not keep up, forcing a temporary shutdown of the batching operation. Some bridging of the cement across the outlet opening in the storage hopper occurred so that no cement was available to the feed hopper, causing additional temporary batching shutdowns. These problems, with no time in the work schedule to rectify them, forced abandonment of the storage hopper scheme after completion of the blowout crater repairs. The storage hopper concept for cement handling is a good approach. Additional work to eliminate the problem of bridging across the discharge openings is needed, however. With fast-discharge bags, the hopper could have been kept full during the repairs.

For the PVC-module fill repair, the storage hopper was replaced with three mobile field storage tanks as shown in Figure 5.34. The rearmost tank (center of picture) is mostly hidden for view. The tanks were set in place and filled from the rubberized bags and cement-bulk trucks. Since each mobile unit has its own compressed-air source for moving the cement out of the tanks, the bridging problem was eliminated. The feed hoppers on the batching unit were positioned as shown in Figure 5.35. The cement was moved pneumatically from each of the three tanks on the unit to a surcharge tank on the end of the truck from which the cement was actually discharged. Each individual tank on the unit could be refilled without interrupting the use of cement from another of the tanks on the unit. This system was highly effective and no further cement supply problems were encountered.

The equipment used to accomplish the batching and pumping is shown in Figures 5.11, 5.36, and 5.37. The units generally conform to the specification in Appendix A except for capacity. Each has a placing rate of 50 yd³/hr. One unit is property of the U. S. Air Force (Figure 5.11) while the other two were leased from a civilian contractor. Only one unit was used for each of the blowout craters. All three units were set up for use on the PVC-module fill crater as shown in Figures 5.38, 5.39, and 5.40. Only two were used, however. Each unit was located to draw cement from one of the three mobile storage units. The foam generators for each unit can be seen in the foreground in Figures 5.38 and 5.39 and in the background in Figure 5.40.

PVC plastic pipe, 3-inch ID, was used as the placing lines. Dual lines were established for each unit. Flexible rubber hose connected the PVC pipe to the batching lines.

5.2.2 Materials. The regulated-set cement used was RC-638 (Table 3.1) and had a specific gravity of 3.02 and a Blaine's fineness (air permeability) of 4800 cm²/gm. Approximately 200 tons of this cement were used for repair of all four craters.

The batching water was obtained from a small pond adjacent to the working area (Figure 5.41). This water was evaluated in accordance with CRD-C 406, "Method of Test for Compressive Strength of Mortar for Use

in Evaluating Water for Mixing Concrete" (Reference 18), for strength-making characteristics when used with regulated-set cement. Mortars made with the pond water developed 10 percent more strength than mortars made with distilled waters. The water was pumped from the pond into a standard water truck which functioned as an intermediate holding tank. All batching units then obtained their water from the tank truck which operated at about 80-psi water pressure. This system worked very satisfactorily. A wire mesh screen was placed around the pickup line in the pond to keep leaves, sticks, and other matter out of the water supply.

The foam concentrate was diluted to the proper concentration in 55-gallon drums (Figure 5.42). A 4 percent solution (by volume) of concentrate in water was used. The foam-liquid pickups for the foam generators were placed in the drums and drew on the supply as needed. The drums were periodically refilled without interrupting the batching. This solution, with the foam generators used, produced a preformed foam, the density of which varied between 4.3 and 4.6 pounds, depending on the generator.

Citric acid solutions of 100 pounds of citric acid (dry, granular) per 32 gallons of water were prepared in 32-gallon standard galvanized garbage cans (Figure 5.42). The venturi-aspirator pickup which fed the citric acid solution into the batching system could be regulated as to how much it picked up under a given set of flow conditions by varying the opening size of the gate valve into the flowing batch water supply. When pumping a neat slurry capping material, each unit pumped approximately 160 gallons or 21.4 ft^3 of material per minute. At a water/cement ratio of 0.55, ideally, 1512 pounds of cement per minute were being used along with 832 pounds (99.8 gallons) of water. If a retardation dosage rate of 0.5 percent citric acid by weight of cement was desired, then 7.56 pounds of citric acid per minute needed to enter into the batching system. At a rate of 100 pounds of citric acid per 32 gallons of water, the venturi opening was set to pick up approximately $2\frac{1}{4}$ gallons of citric acid solution per minute. These settings were determined prior to the repair operation.

5.2.3 Blowout Crater Repairs. Three Type 2 blowout craters (Figure 1.3) were repaired using three different techniques. The craters were approximately conical in shape, 12-15 feet in diameter and 3-5 feet deep. Figure 5.43 shows one of the craters. This crater was repaired by pushing some debris into the crater and removing the remaining debris from the working area. The edges of the pavement were then roughly shaped by additional pavement breakage into a rectangular shape. A fill aggregate was then placed on top of the debris and the entire mass compacted with a towed vibrating roller (Figure 5.44) to a subbase level approximately 11-12 inches below the existing top surface of the adjacent pavement. Since the center of this crater was very near the edges of the pavement, two edges of the crater were not in the pavement and had to be formed with boards (Figure 5.45). Plastic sheeting was used to prevent the concrete from flowing under some of the form boards that were not as deep as the desired pavement thickness. Earth material was also used. Only a neat regulated-set cement capping material was used in this repair and it was pumped approximately 125 feet through the 3-inch-diameter PVC pipe shown in part in Figure 5.46. A flexible "snout" was placed on the end of the PVC pipe to facilitate movement around the repair area (Figure 5.47). Filling proceeded (with some minor interruptions) until stopped by an extremely severe thunderstorm. The section was not quite full at that time and is shown in its hardened condition in Figure 5.48. Figure 5.49 is a close-up of the end of the section that was filled and screeded before the rain. The screeding was easily accomplished using a 2- by 6-inch board.

This neat slurry cap had a water/cement ratio of 0.56 and used approximately 0.6 percent citric acid retarder by weight of cement. Approximately 8 yd³ of material were placed. The placement had numerous minor interruptions caused by inability to get cement out of the large bins (Figure 5.31) and into the feed hoppers on the batching equipment. When these stoppages occurred, the placing lines had to be flushed out with water to prevent the cement from hardening in the lines.

The following day, the filling of the smaller section (approximately

9 by 16 feet) adjacent to the first section (Figure 5.48) was attempted along with the filling of the remainder of the larger section not filled the previous day. The same mixture was used. Placing was again interrupted numerous times by cement handling operation at the batching unit. Screeding again was no problem. One hour after the pumping of the smaller section was complete, a load-cart with 50,000 pounds of blocks stacked on the cart was driven onto the section when the concrete was approximately 90 minutes old (Figure 5.50). The load was transmitted from the cart to the concrete by a steel load plate, the area of which simulated that of the tireprint of the F-4E tire. The total load actually transmitted to the tireprint was approximately 32,500 pounds. Measurements of deflections of the concrete slab were made using dial gages mounted on a rigid reference beam supported off the lower edge (Figures 5.50 and 5.51). No measurable deflections were observed.

The second blowout crater (Figure 5.52) was repaired by dumping debris into the lower zones of the crater and covering it with select fill aggregate. The entire section was then compacted with a towed vibrating roller. The surface of the select fill after compaction, with some grading, was even with the top surface of the adjacent pavement. The fill aggregate was approximately 20-24 inches thick at this point. Figure 5.53 shows the top surface of the aggregate. Neat regulated-set cement slurry was then pumped 162 feet through a 3-inch-diameter PVC placing line and spread over the surface of the aggregate fill (Figure 5.54). The slurry percolated down through the aggregate and, upon hardening, solidified the upper portion of the aggregate fill. Depth of penetration was estimated to be 9-12 inches. The slurry had a water/cement ratio of 0.55 (by weight) and used citric acid retarder at a dosage of 0.5 percent by weight of cement. It took approximately 4-5 minutes to complete the pumping operation with approximately 2 yd³ of slurry being used. Screeding was accomplished using a 5/8-inch water hose, partially filled with water, which was dragged across the surface of the concrete (Figure 5.55). Initial hardening occurred within 15 minutes with continuous water-curing being applied for an additional hour (Figure 5.56). This curing was aimed at preventing early-age

cracking in the slab caused by drying of the slurry surface in the extremely hot ambient temperatures. A small amount of this cracking was observed in the first blowout crater repaired. The crater cap did not crack and was able to sustain truck traffic 90 minutes after the repair.

The third and last blowout crater was repaired by placing a small amount of debris on the bottom of the crater. Cellular concrete was then placed on top of the debris as the base course material with a neat regulated-set cement slurry for the capping material. Figure 5.57 shows the crater with the debris in it. The boards were placed to establish grades and elevations and also for screeding purposes. Figure 5.58 shows the cellular concrete being placed in the crater. The pumping distance was 62 feet. The cellular concrete was to have a water/cement ratio of 0.55 (by weight) and a density of 85 pcf. Due to the same cement handling problems mentioned previously, not enough cement was getting into the concrete during batching such that the density of the cellular concrete was reduced to 55-60 pcf, the cement content lowered, and the water/cement ratio significantly increased. All these factors contributed to reductions in strength of the cellular concrete. When the cellular concrete level was approximately 8 inches below the desired surface (Figure 5.59), the preformed foam was left out of the batching and a neat slurry cap placed (Figure 5.60). The cement handling problem had been corrected earlier. Screeding was done using a 2- by 6-inch board. Figure 5.61 shows the finished surface. Hardening occurred within 15 minutes. Approximately 18 hours later, the same loading procedure as that used on the first blowout crater was applied to this repair. At 30,000 pounds of load on the steel plate, a punching shear failure occurred in the capping material due to the failure of the cellular concrete base material. This was expected due to the low-strength material that ended up in the base course. When the base material is properly made with the necessary CBR strength (Section 2.2.2), this type of failure should not occur. Other than the cement handling problem, the placement of the cellular concrete and the capping material went very satisfactorily with no other problems occurring.

5.2.4 PVC Pipe Module Fill Crater Repair. The crater to be filled with the regulated-set cement cellular concrete and the PVC modules was created by detonation of a 750-pound bomb and then mechanically shaped to produce a crater of approximately 38 feet in diameter, 11 feet deep, with a 10-foot-diameter flat bottom. The crater sides had a 1.22 slope. The repair procedure closely followed that used at WES for the PVC pipe modules (Section 5.1.2) but was conducted on a much larger scale.

A total of 27 modules, 8 constructed of 12-inch-diameter pipes, 19 constructed of 10-inch-diameter pipes, were used in the repair. The wall thicknesses on the 10- and 12-inch-diameter pipes were 0.20 inch and 0.24 inch, respectively. Details on the pipes, their assembly, and module testing can be found in Reference 25. Figure 5.62 shows the modules preassembled. The modules were to be stacked in the crater in three layers with only 1 module in the first layer, and 7 and 19 modules in the second and third layers, respectively. The 12-inch-diameter pipe modules were used in the bottom two layers while the 10-inch-diameter pipe modules were used in the top layer only. All modules were 3 feet tall.

Approximately 25 military personnel performed the actual repair. Three men were assigned to each of the two pumping units: one man operated the unit, one kept the feed hopper full of cement, and the third took care of the foaming agent, citric acid solution, and foam generator. Four men were assigned to each placing line. Usually, only two men were required to handle and manipulate the line at the crater, but if the line, full of material, had to be moved any distance, all four men were needed. Six men placed the modules using a 35-ton-capacity hydraulic crane. The other five men assisted when needed. The module crew also assisted in the capping operation.

Figure 5.63 shows the modules after being moved to the repair area after the debris had already been removed. Each module was covered with a plastic sheet on its top surface to prevent the concrete from filling the pipes once they were overtopped by the concrete. A base of regulated-set cement capping material was placed on the flat bottom of

the crater and the first module set in it. This material hardened rapidly and effectively cut off flow of the material at the bottom of the pipes from the outside of the module to the inside of the pipes. Cellular concrete of approximately 40-45 pcf density was then placed around the module. A layer of capping material was then placed on top of the first module and the second layer of modules put in place. Figure 5.64 shows the modules in place with the cellular concrete rising around them. Additional capping material was also placed on the top of these modules (Figure 5.64 and 5.65). Figure 5.66 shows the final surface of the cellular concrete with a few of the modules projecting out of it.

The mechanical shaping of the crater should have permitted easy stacking of the modules, but this was not the case. The second and third layers did not fit perfectly; a small module was substituted for a large module in the second layer and a large module was left completely out of the third layer. Some reshaping of the bank was necessary to get all of the third-layer modules to fit.

Only a portion of the cap would be below the original grade of the pavement. This was not intentional but the stacking of the presized modules brought the elevation too high in the crater to obtain a sufficient cap thickness level with or below the existing pavement surface. To compensate for this, form boards were partially constructed adjacent to the crater and moved into place over the crater (Figure 5.67). The formwork was then completed and roughly leveled. Five segments or lanes, each 10 feet wide, were formed. Each lane was to be placed separately. Polyethylene sheeting (Figure 5.68) was used to prevent the capping material from flowing from lane to lane. The sheeting concept was only partially successful and soil had to be used as dikes in some locations.

Figure 5.69 shows the placement of the regulated-set cement cap. All form boards were left in place. The lanes were cast one at a time starting with the center lane. Both batching units pumped material into the same lane, each working from different ends toward the center. In retrospect, it would have simplified screeding if the material had been placed from the center to the outside of the crater. Screeding from the outside to the center from both ends left a surplus of material with

no ready place to dispose of it. All pumping proceeded smoothly. Screeding and leveling were done with 2- by 6-inch boards using the form boards as guides. Water was continuously sprayed on the screeded surface from the time screeding was completed for about 1 hour. Figure 5.70 shows the completed cap 30 minutes after the last lane was filled. All lanes could sustain foot traffic within 10-15 minutes after they were completed.

The finished surface was relatively level but was rough in texture because it had only received a rough screeding. A few shrinkage cracks occurred in areas which did not receive water-curing promptly after hardening but the cracks were not serious. Cracking of this type can always be expected in neat paste materials. The use of sand in the mixture as described in Section 5.1.2 will greatly reduce the possibility of this happening both at this early age and at later ages.

The repair procedure went very smoothly for a first-time operation on a full scale. The total repair time was 5 hours, 4 minutes. Approximately 2 hours of this was used to place the modules. Pumping continued during this time. All pumping stopped for approximately 1-1/2 hours while the form boards were being assembled and set for the capping material. This time was longer than would be expected if the crater had been filled to a proper elevation so that such an elaborate forming system was not required.

Two loading tests were conducted on the repaired crater. The first was a plate load test conducted on the center of the cap over the approximate center of the module stack about 4 hours after the cap was completed. A truck trailer and jack were used to load the plate. A load of 50,000 pounds was placed on the truck which, in turn, caused the plate to be loaded to approximately 20,000 pounds. The plate displaced approximately 1-1/4 inches into the capping. Upon jacking the truck down to the surface of the cap to remove the plate, a circular crack approximately 13 feet in diameter occurred in the cap. The failure appeared to be caused by diagonal tension.

The second test was conducted 1 hour after the first and involved driving a load cart representing an F-4E aircraft onto the repaired

crater. This cart exerted a 30,000-pound load to the pavement through an F-4E tire inflated to 265 psi. The tire of the load cart penetrated the cap until stopped by the axle. The failure was a classical punching shear type. Examination of the hole after the cart was removed revealed that the PVC pipes had softened considerably due to the heat developed by the hydration of the cement and were offering no support to the cap. In effect, the cap was acting as an unreinforced slab spanning an empty hole except for some edge support provided by the cellular concrete. This lack of subgrade support from the PVC modules also explains the failures during the load plate test. Strain gages on the PVC pipes indicated that the pipes had compressed under the load and had retained the deflected shapes upon removal of the load.

As mentioned in Sections 5.1.1 and 5.1.2, the heat development in large sections of regulated-set cement concrete is substantial. The temperature of the air in the loaded pipes was 220°F. Extremely warm temperatures were noted for the PVC module tests conducted at WES (Section 5.1.2), but softening of the pipes was not observed because it was not looked for in the test. The PVC pipes at WES appeared hard but were never loaded. The maximum temperature developed in the Tyndall crater was approximately 30°F greater than in the WES crater. This is probably due to the larger volume of cement used and the fact that the temperature of the mixture at placement at Tyndall was 18°F greater than at WES.

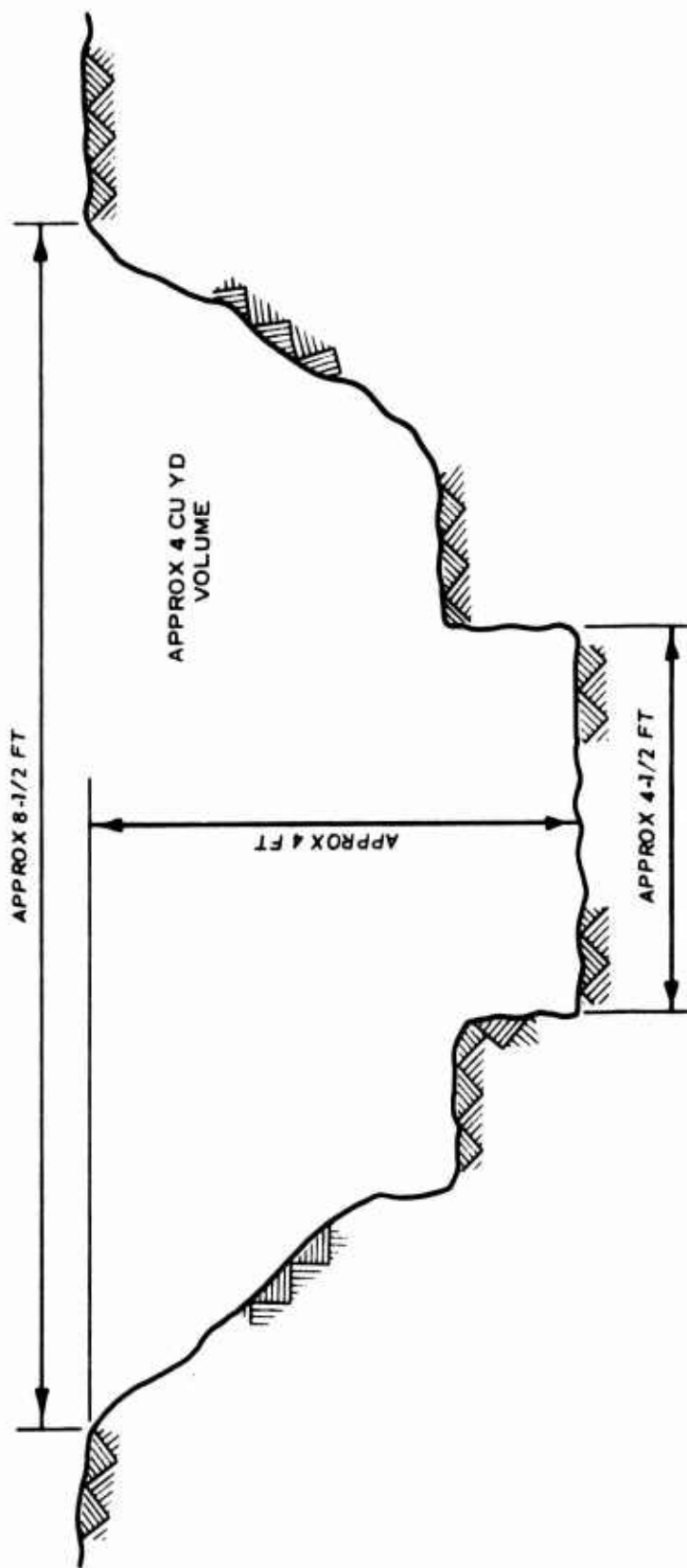


Figure 5.1 Cross section of small simulated crater.



Figure 5.2 The simulated crater.



Figure 5.3 Concrete surface at the start of the 50-pef cellular concrete placement.

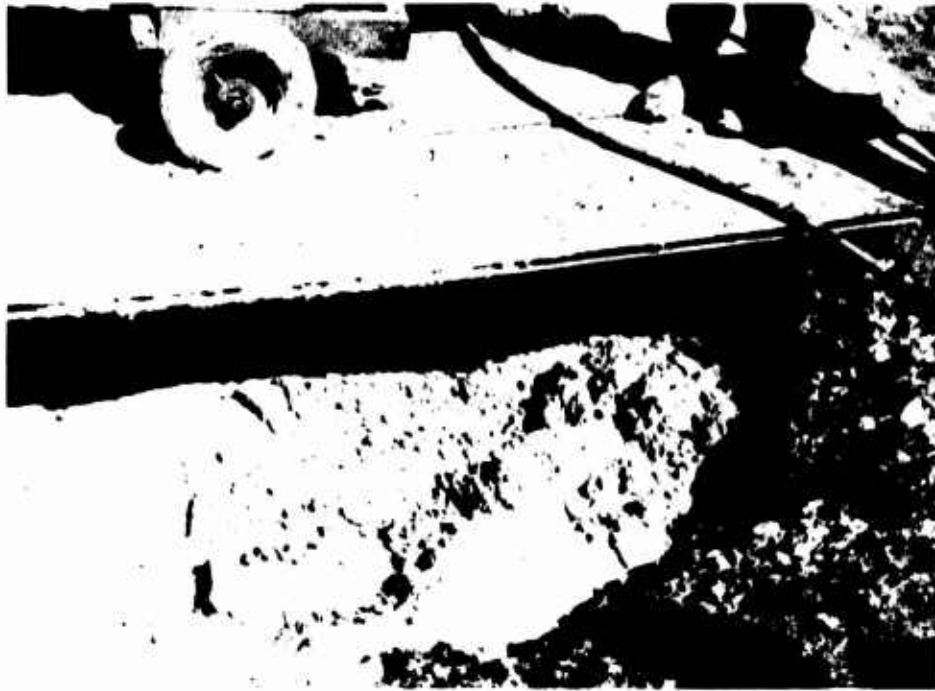


Figure 5.4 Concrete surface immediately after completion of the 65-pcf cellular concrete placement.



Figure 5.5 Concrete surface 10 minutes after completion of the 65-pcf cellular concrete placement.



Figure 5.6 Placement of the 85-pcf cellular concrete.



Figure 5.7 Repair surface after the 110-pcf neat slurry placement.



Figure 5.8 Repair surface shortly after additional capping material added.

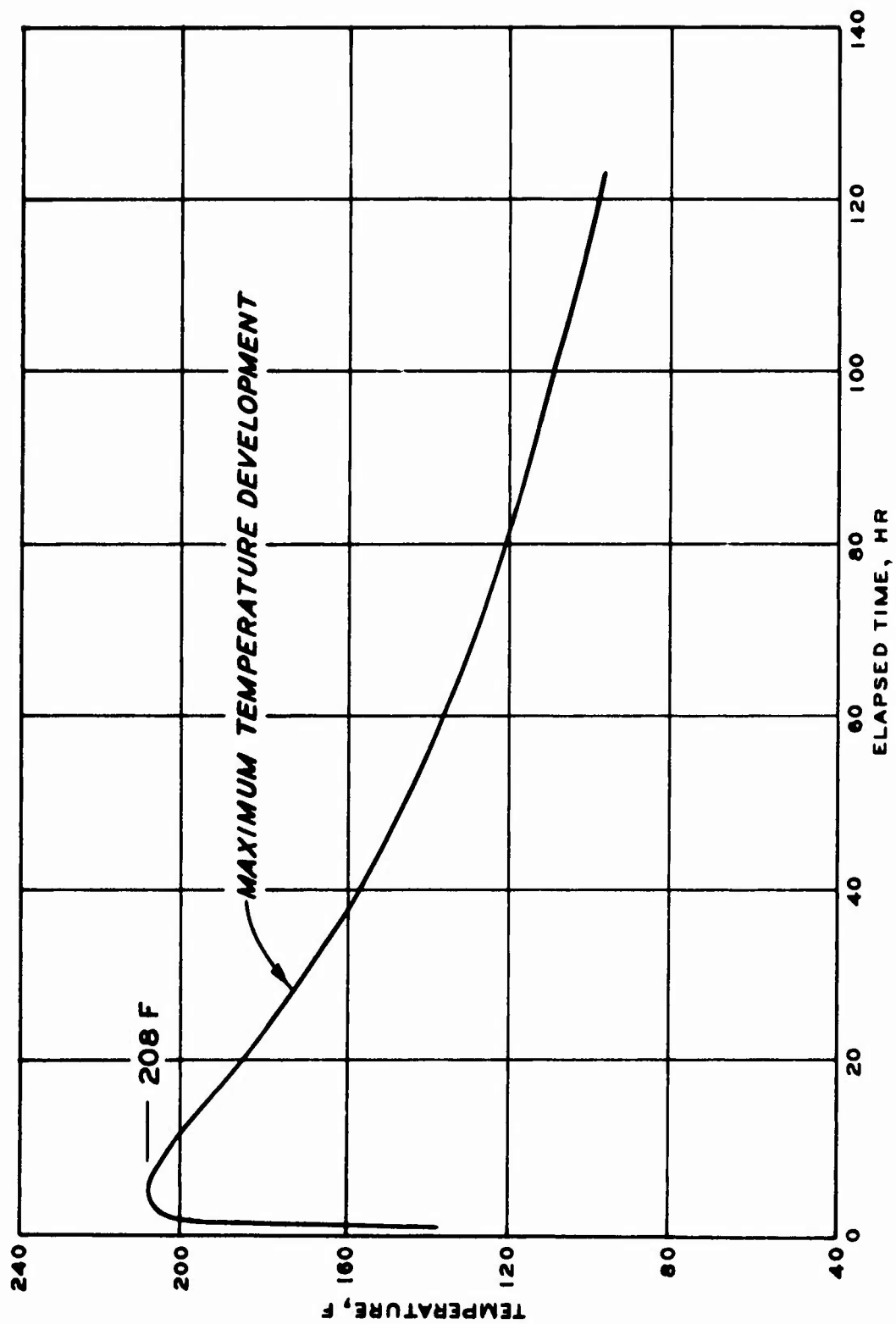


Figure 5.9 Maximum temperature development versus time after placing relation for simulated crater repair.

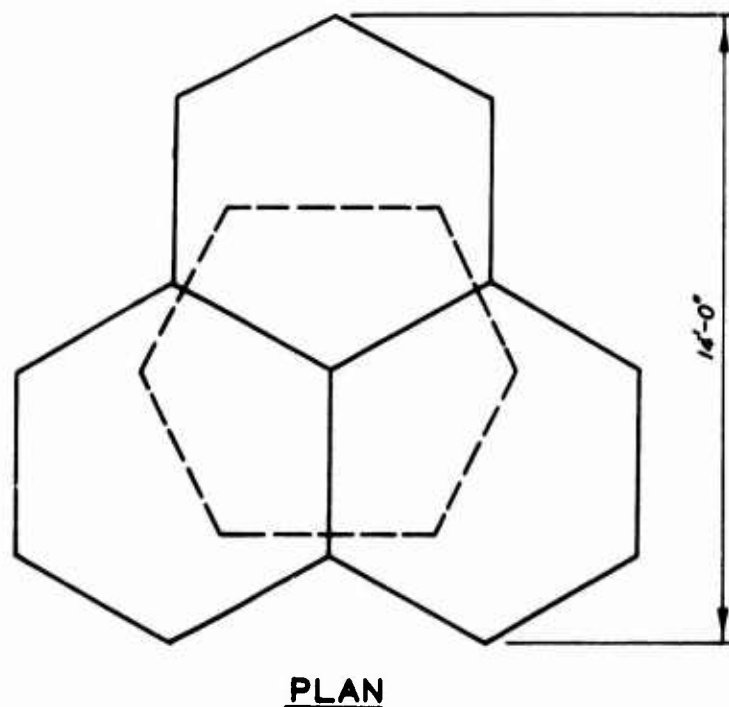
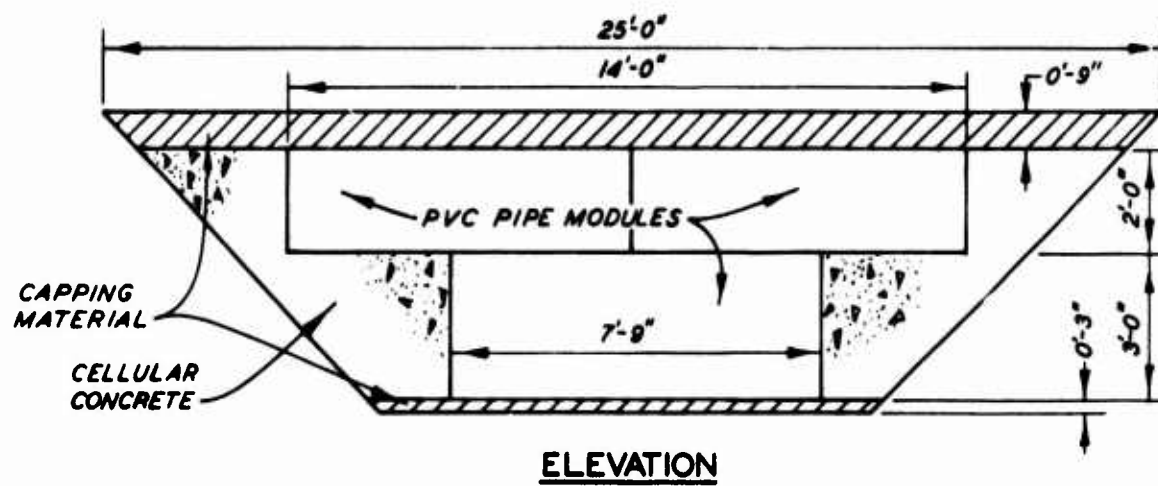


Figure 5.10 PVC pipe module repair scheme.



Figure 5.11 Batching and pumping unit - WES one-sixth-size crater trials.



Figure 5.12 Batching operation using rubberized storage bags for cement handling.



Figure 5.13 Field storage tank cement delivery system.

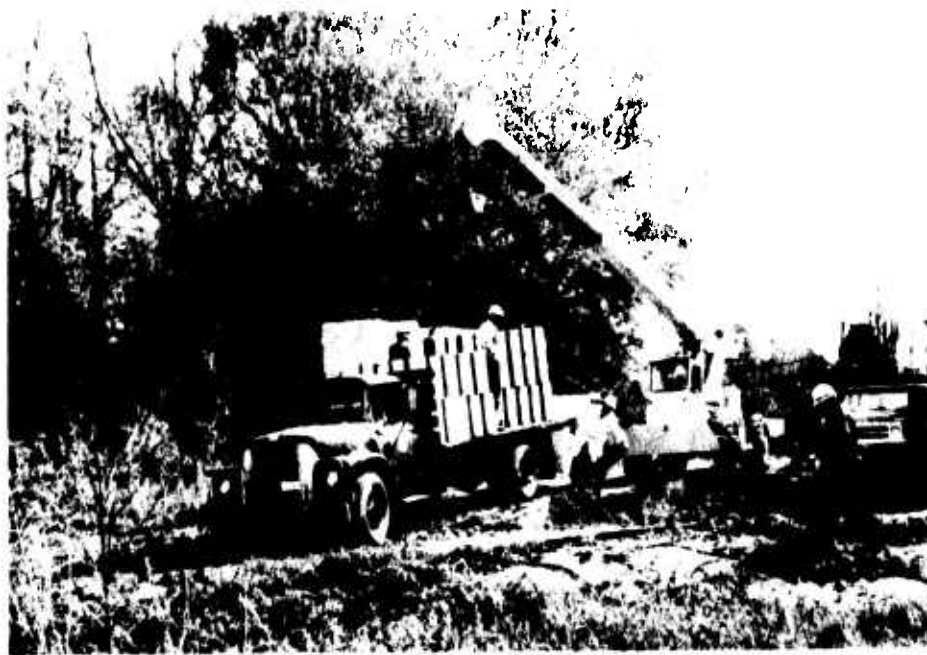


Figure 5.14 Unloading of PVC pipe modules.

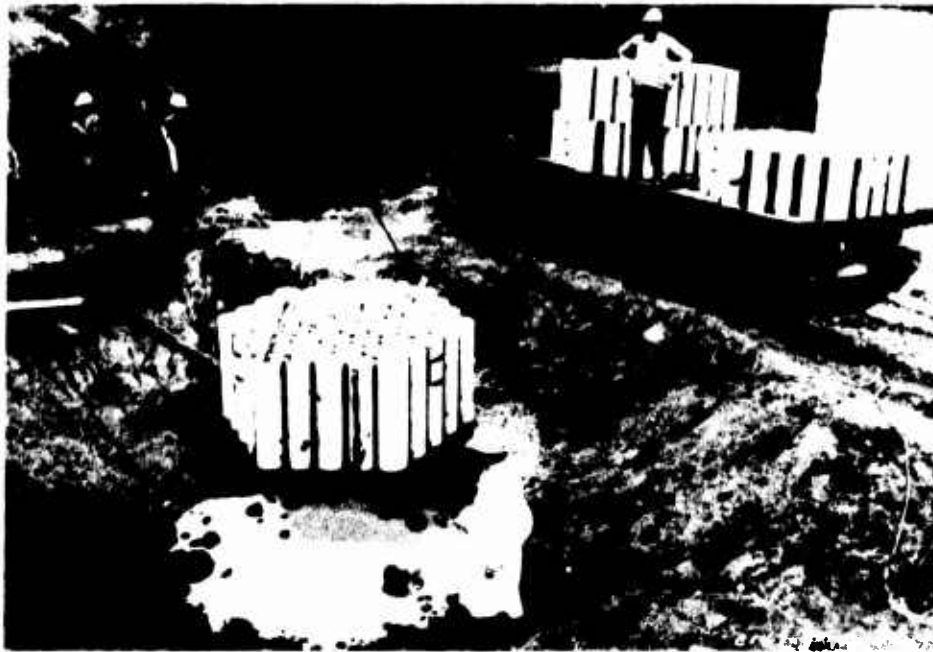


Figure 5.15 Placement of the bottom PVC pipe module.

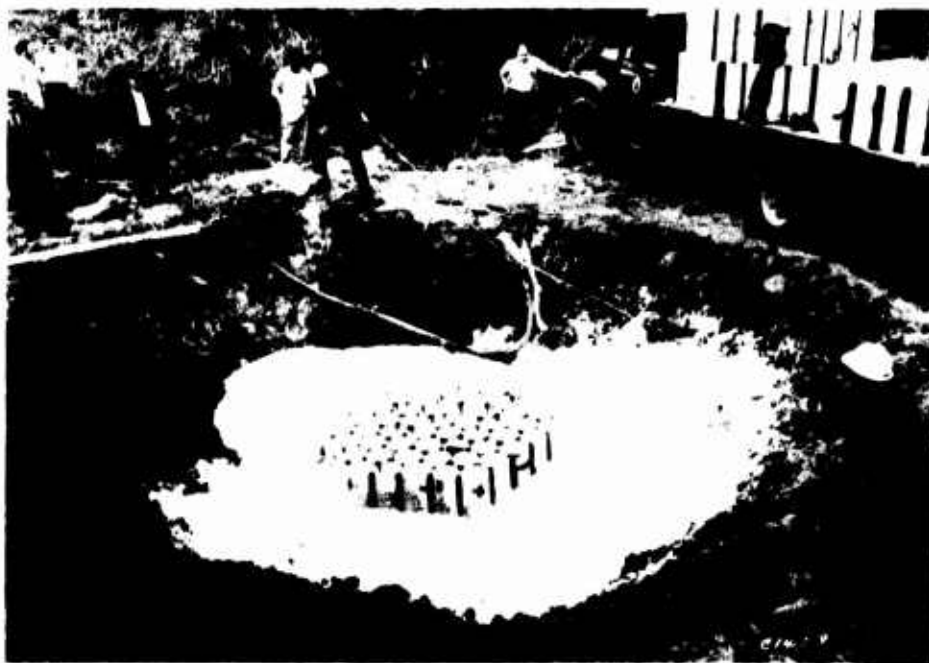


Figure 5.16 Placement of cellular concrete around bottom module.

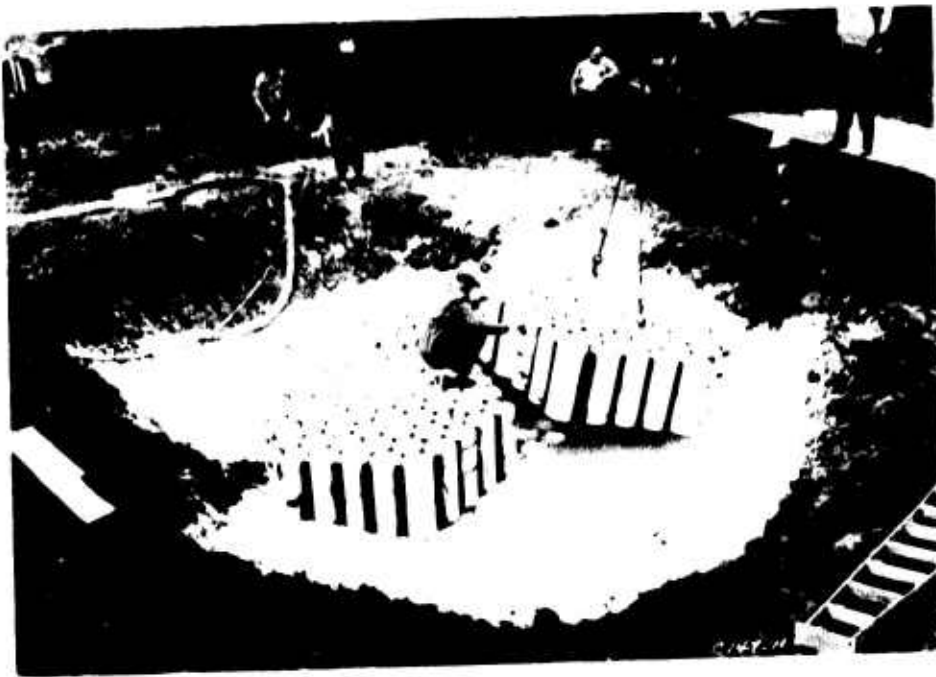


Figure 5.17 Positioning of top layer of modules.

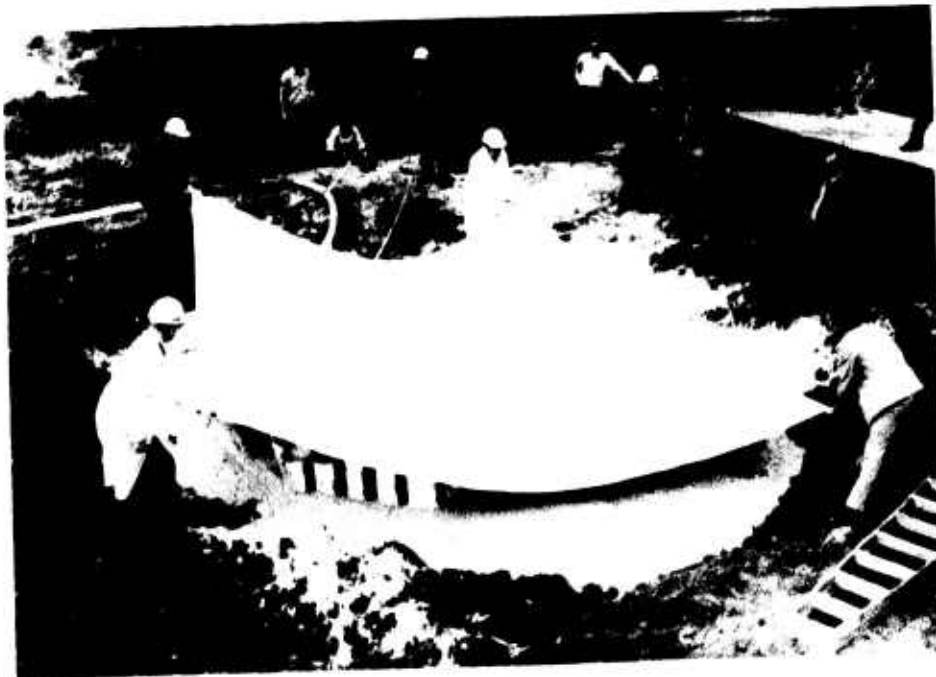


Figure 5.18 Covering the pipe openings with a nylon sheet.



Figure 5.19 Completed sealing of module system.



Figure 5.20 Completion of cellular concrete placing.



Figure 5.21 Crater for the cellular concrete backfill test.



Figure 5.22 Start of the cellular concrete backfill repair.



Figure 5.23 Crater half-filled with cellular concrete backfill.

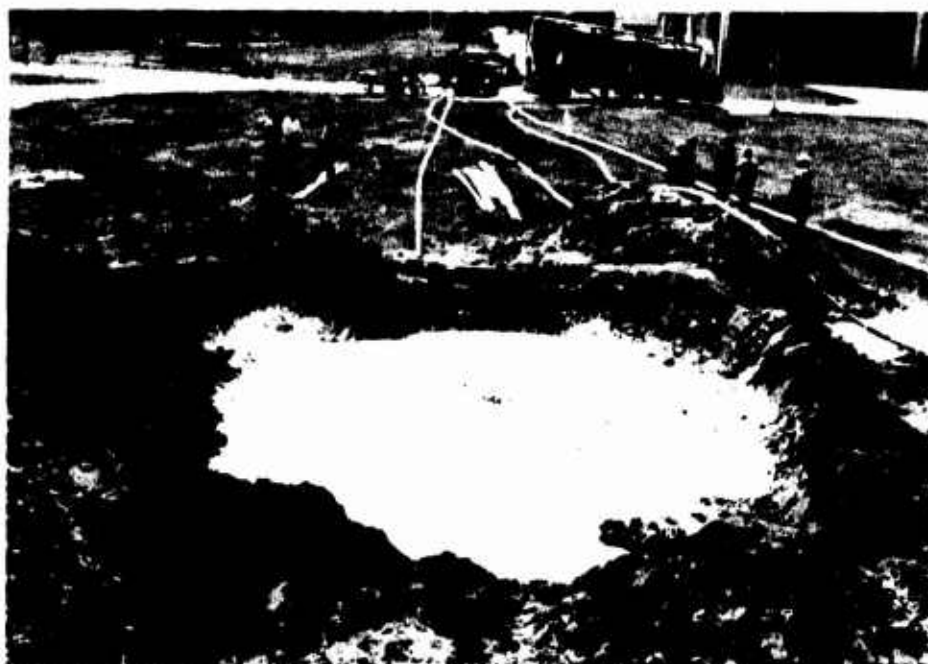


Figure 5.24 Top surface of cellular concrete backfill.



Figure 5.25 Placement of joint boards.



Figure 5.26 Placement of the capping material.



Figure 5.27 Finished repair for the cellular concrete backfill test.



Figure 5.28 Surface of repair showing some drying shrinkage cracking.



Figure 5.29 Severe drying shrinkage cracking.



Figure 5.30 Small slab preparation.



Figure 5.31 Gravity-feed cement storage hopper.

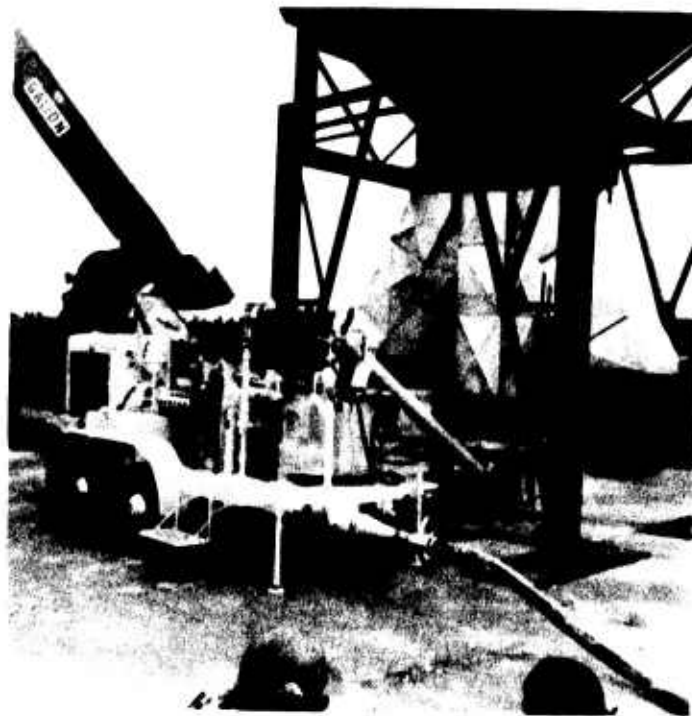


Figure 5.32 Batching and pumping equipment arrangement.



Figure 5.33 Storage hopper-feed hopper arrangement.

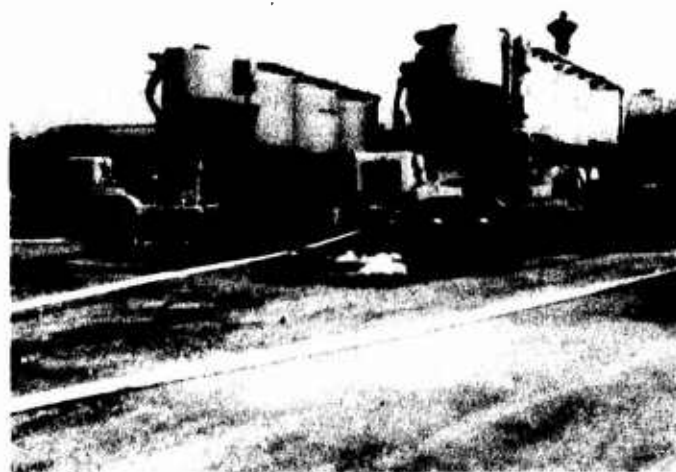


Figure 5.34 Mobile field storage tanks.



Figure 5.35 Cement feed arrangement.



Figure 5.36 Batching and pumping unit 1.



Figure 5.37 Batching and pumping unit 2.

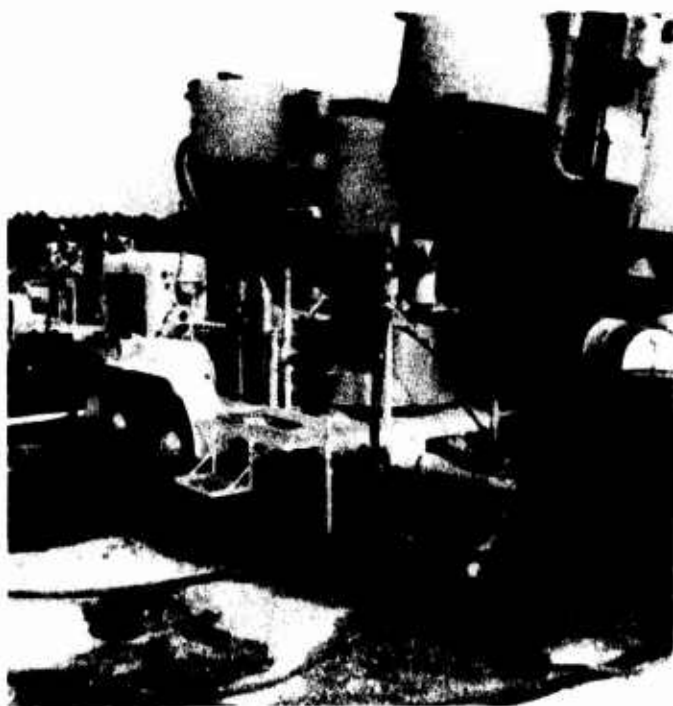


Figure 5.38 Unit 1, foam generator, and cement supply arrangement.



Figure 5.39 Unit 2, foam generator, and cement supply arrangement.



Figure 5.40 U. S. Air Force unit, foam generator, and cement supply arrangement.



Figure 5.41 Water supply impoundment.



Figure 5.42 Holding tanks for foam solution and retarder concentrate.



Figure 5.43 Blowout crater 1.



Figure 5.44 Vibratory-roller compaction of fill aggregate.



Figure 5.45 Finished surface of base course.



Figure 5.46 Placement of neat cement slurry cap.



Figure 5.47 Flexible hose for ease of movement during placing.



Figure 5.48 Incomplete repair surface.



Figure 5.49 Rough screeded top surface of repair.



Figure 5.50 Loading of repaired crater by cart loaded with 50,000 pounds of blocks.



Figure 5.51 Loading of repaired crater. Note reference beam in foreground.



Figure 5.52 Blowout crater 2.



Figure 5.53 Select fill aggregate placed to existing pavement surface.



Figure 5.54 Placement of slurry on fill surface.



Figure 5.55 Screeding of repair surface.



Figure 5.56 Water-curing of repair surface.



Figure 5.57 Blowout crater 3.



Figure 5.58 Placement of cellular concrete fill.



Figure 5.59 Top surface of cellular concrete fill.



Figure 5.60 Placement of slurry over cellular concrete fill.



Figure 5.61 Completed surface of blow-out crater 3 repair.

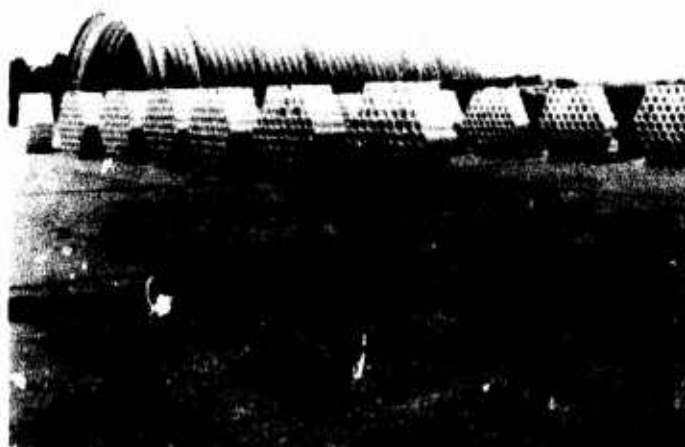


Figure 5.62 PVC pipe modules.



Figure 5.63 Sealed modules ready for placement in the crater.



Figure 5.64 Placement of cellular concrete around modules.



Figure 5.65 Placement of neat slurry between layers of modules.



Figure 5.66 Top surface of cellular concrete fill placement.



Figure 5.67 Form and joint boards being assembled.

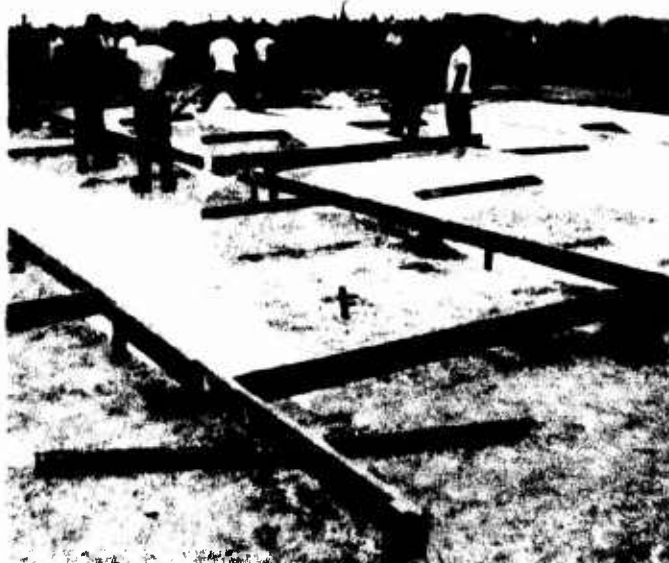


Figure 5.68 Form and joint boards in place over backfilled modules.



Figure 5.69 Placement of neat slurry capping material.



Figure 5.70 Top surface of completed repair.

CHAPTER 6

DISCUSSION

6.1 THE REPAIR CONCEPT

It has been generally assumed that only three major craters formed by 750-pound bombs would have to be repaired to produce the desired operational surface on a runway. Depending on the size and type of munitions used and the intensity of attack, the runway may, in fact, be covered with many different sizes and types of craters such as those shown in Figure 1.3. A repair procedure, such as that described in Section 1.2 and specified in Reference 6, is effective primarily on large craters but does not have the flexibility to readily adapt to variations in crater size and number. A runway surface covered with 15 to 20 craters of 10- to 15-foot diameter and depths of 3 to 6 feet or a runway with a number of camouflet and spall craters could not be repaired in 4 hours time with the present procedure. The adaptability of the regulated-set cement repair scheme to any damage situation is one of its two best assets. The other is permanence of the repair. The scheme can also be applied to any type of runway surface, i.e. rigid, flexible, or expedient.

The suitability of the regulated-set cement repair scheme for repairing small craters was shown in Section 5.2.3. The potential to pump the cellular concrete or capping material several hundred feet allows the batching and pumping equipment to be set up in locations where the placing lines could be readily moved from one small crater to another, thereby filling craters with a minimum of downtime for the batching equipment. Types 5, 6, and 7 craters (Fig. 1.3) could easily be filled by simply extending the placing lines through the opening in the pavement. Type 1 spall craters (Fig. 1.3) could be repaired almost as fast as the placing lines could be moved. A simple screeding using the surrounding existing pavement as a guide would finish this repair to the desired wearing surface level.

The repair procedures discussed in Reference 6 are remedial in

nature and resultant repair must be upgraded to permanent at a later date. This will involve the removal of the landing mat, the upgrading of the fill material to the desired bearing strength either by further compaction or removal and replacement, and then the placement of a permanent pavement surface, level with the surrounding existing pavement surface. The repair made with regulated-set cement is a permanent repair. The cellular concrete fill, when properly designed, will develop more bearing strength than would generally be required by a rigid airfield pavement. It also fills all the major voids in the lower portion of the crater normally associated with just simple dumping of debris into the crater and a minimal compaction effort. The capping material produces a strong, durable, structural wearing surface that can be finished level with the existing pavement. The joint boards in the repair, if any, would have to be removed at a later date and replaced with a more permanent joint material.

The repair concept using regulated-set cement is outlined in Figure 6.1. The detail of needed personnel into repair responsibilities is shown in Table 6.1. The damage assessment and determination of the craters to be repaired in order to provide a usable surface 50 feet wide and 5000 feet long should be done by personnel specially trained for this responsibility; it should not be left up to the construction supervisor for the repair. When the proposed repair team outlined in Table 6.1 arrives on the runway, craters to be repaired should already have been determined. The team then breaks into four major crews for the repair: runway cleaning crew, hauling crew, crater repair crew (one for each of the three major craters), and the new centerline crew. These job details are based on the manpower deployments used in the existing repair procedure (Reference 6) and have been modified to satisfy the requirements of the regulated-set cement repair concept. Some of these activities are of short duration, and the personnel involved can be utilized in other activities when not performing their own. The runway cleaning crew consists of sweeper operators who clean the smaller debris, mainly ejecta, from the majority of the runway surface, and a front-end loader (FEL) operator who removes any larger

pieces of debris. The sweepers can be either rotary or vacuum types, but vacuum is preferred. The rotary sweeper tends to relocate the debris on the pavement without actually removing it. The FEL can also be used to prepare the perimeters of any blowout or spall craters that may also have to be repaired along with the major craters. Upon completion of the majority of the cleanup, some of the sweeper operators can begin the assembly of the joint boards for the Zone 3 crater repair.

The hauling crew is used to move cement and sand from their storage areas to the working areas. The exact number of personnel required and their particular skill will depend on how the cement is stored and handled. The requirements in Table 6.1 assume the cement will be stored in rubberized bags. This requires an increase in mobile crane operators and helpers from one each in the present repair procedure (Reference 6) to four each in order to provide a system for handling the cement at each crater in addition to a mobile crane at the cement storage area. If the cement were stored in mobile field storage tanks, the crane operator and helper would remain at one each but the tractor-trailer operators would be increased to nine. The present repair procedure requires more dump trucks and dump truck operators than required in Table 6.1, but three times more aggregate must be moved in that procedure than in the proposed procedure. The dump truck operators, after moving the sand for the Zones 2 and 1 repairs, and the tractor-trailer operators after completing their assignment, can assist in the preparation of the joint board assemblies.

The crater repair crew includes the placing-line helpers in the crater, a FEL operator and a dozer operator (who remove debris and prepare the crater perimeter for repair), and the pumping equipment operators and their helpers. Each crater should have access to four batching and pumping units: three to use and one backup unit. Each operating unit will need an operator, a helper to assist in hose connections and ensure adequate supplies of water, retarder, and foaming agent in the auxiliary supply systems, and a material delivery systems helper who will ensure that adequate supplies of cement and sand are available for continuous operation of the batching unit. Crater helpers will lay

and connect all placing lines and be responsible for their maintenance and deployment in and around the crater both before and during the actual filling of the crater.

The new centerline crew establishes a visible line system on the repair to aid aircraft in landing and taking off. This is essential to ensure that the aircraft does not wander off the prepared pavement surface.

The total number of personnel required in the proposed regulated-set cement repair scheme is 92 (see Table 6.1). This total may vary slightly in either direction, depending on the techniques and equipment used to store and haul materials. The amount of personnel should vary only in the size of the hauling crew. This team total of 92 is a reduction of 29 personnel (25 percent over that required in the present repair procedure (Reference 6)).

The rapid repair equipment package must be modified to include the following equipment: one less sweeper, one more FEL, five less dump trucks, three more mobile cranes, and twelve batching and pumping units. These requirements are based on using rubberized bag storage for cement. Other modifications will be necessary if other storage systems are used. Water pumps and other smaller items must be added to the construction equipment, while equipment such as vibratory compactors will be eliminated. Once a final repair scheme is selected, a review and revision of the present equipment and materials repair kit is essential.

6.2 CEMENTING MATERIALS

Although this report is concerned primarily with the use of regulated-set cement, the possibility of using the proposed repair scheme with different organic and inorganic cementing materials exists. The following discussion includes comments on the more common cementing materials often proposed when the problem of rapid repair is discussed.

If a binder material is to be effective in a bomb-damage repair scheme, it must harden and develop strength very rapidly, be durable, and be relatively inexpensive. It should also be able to be made and placed over a wide range of temperatures. Many polymeric materials

can satisfy all these requirements except expense. For the volumes of materials anticipated, even if used only in Zone 3, the costs of the polymers would be extremely prohibitive. Some inorganic, hydraulic cements can also satisfy some of these requirements and most of them are not much more expensive than normal portland cement. These include calcium sulfate (gypsum) cements, high-alumina cements (HAC), silico-phosphate cements, and regulated sets cements. Silico-phosphate cements are primarily used as dental cements and are expensive. Modifications of these cements to reduce costs have reduced the cost to approximately twice that of normal portland cement (Reference 1), but in this form they are not commercially produced and hence will not be discussed further in this report.

A large number of gypsum cements have been developed for specific industrial uses. All are essentially alpha gypsum (gypsum hemihydrate, plaster of paris, $\text{CaSO}_4 \cdot 1/2\text{H}_2\text{O}$), differing in granular shape, density, and in additives. Common names for these cements are Hydrostone, IP, Hydrocal, Ultracal, and Fast-Fix. Fast-Fix cements are blends of gypsum and portland cements and have been considered for use in the rapid repair of runways (References 9, 10, and 29). Some formulations have been reported as having setting times of 12-15 minutes with 30-minute compressive and flexural strengths of 4000 and 700 psi, respectively (Reference 9). A number of simulated craters were repaired by percolating Fast-Fix slurries through pea-gravel or crushed rock allowing a top thickness of 1 or 2 inches of neat slurry. All repairs with a total thickness of 12 inches (11 inches of gravel) successfully withstood single wheel rolling loads of 29,000 pounds with tire pressures of 275 psi. The CBR of the subgrade was 4 (Reference 29). However, the Fast-Fix formulations, while performing satisfactorily structurally, have not proved durable. Attempts to improve this durability have been made using latex modification but only limited success was achieved (Reference 2). Special batching and pumping equipment have been developed for the use of Fast-Fix slurries in rapid runway repair. Fast-Fix cements could also be foamed into cellular concretes, if desired, but would require foaming agents different from those described in Section 3.5.

A new, fast-setting, rapid-strength gaining cement, called VHE cement has recently been developed by the U. S. Gypsum Co. and reportedly is a hydraulic cement combining the best properties of gypsum plaster and portland cement. VHE cement can be manufactured in conventional portland cement plants with essentially the same ingredients but in different proportions than those used for portland cement. The accelerated setting time of the cement is achieved by burning into the cement clinker a controlled amount of anhydrous calcium sulfoaluminate. Because the cement is new, little published data are available. It has been reported, however, that initial setting times vary from 20-30 minutes with mortar cube compressive strengths of 2000-4000 psi being developed at 3 hours age. (Reference 30). Flexural strengths from 600 to 700 psi at 8 hours age were also reported. Information on long-term durability was not available although some short-term accelerated freeze-thaw test results showed that properly air-entrained VHE cement concrete was frost resistant.

HAC's have been successfully used as rapid hardening, high early-strength materials. HAC, which is also known as calcium-aluminate cement, is produced by pulverizing clinker consisting essentially of hydraulic calcium aluminates resulting from the fusing or sintering of a suitably proportioned mixture of aluminous and calcareous materials. On the average, the setting times of HAC are found to be slower than those of most portland cements, yet the general opinion is that HAC is fast-setting (Reference 31). This opinion is not based on the behavior of the cement in standard setting time tests, but usually on observation of mortar and concrete under site conditions. Some confusion between the setting and the hardening properties is also evident. Initial setting times vary between 2 and 8 hours with 4 hours being a reasonable average. Final setting times closely follow the initial set.

Very high mix temperatures or contamination with lime, plaster, portland cement, etc., can, of course, cause genuine quick-setting, but experience shows that many examples of apparently premature set are due to the fact that HAC mortars or concretes do not hold water as well as

the corresponding portland cement mixes, and, in some instances, this greater tendency to "bleed" can produce an apparent stiffening or surface consolidation before the initial set is approached.

There is, however, a great difference in the behaviors of portland cement and HAC once the initial set has been reached. The development of strength in the portland cement mix is still very slow after this stage, while the HAC mix develops strength so rapidly that it becomes rigid shortly after setting. There is therefore some justification in the statement that the practical "working time" of portland cement is longer than that of HAC, even when the setting time of the latter cement is slower.

Contrary to the behavior of portland cement, the setting time of most HAC's in the temperature range of 64 to 86°F becomes progressively slower as the temperature rises and only above 86°F does the rate set accelerate again. The setting times between 34 and 64°F are fairly constant but tend to be slightly faster at approximately 45°F (Reference 31).

HAC's can be manufactured with either low or high silica contents. The lower silica content HAC's are used to a greater extent for structural purposes when high early strengths are required. About 80 percent of its ultimate compressive strength is achieved at 24 hours age. Compressive strength of 1000-2000 psi are possible within a few hours after setting.

In using HAC as the cementing binder in the repair concept of this report, consideration must be given to the possibility of strength degradation with various combinations of moisture and temperature (References 31 and 32). Hexagonal hydrates form at ordinary temperatures in HAC; these hydrates are metastable and normally persistent at ordinary temperatures. They contribute significantly to the strength development. Under hot, wet conditions, however, these hydrates can convert into stable cubic hydrates. The cubic hydrate has a much lower density than the hexagonal hydrates from which it is formed. Hydrate conversion, together with a simultaneous aging of the alumina gel, is believed to increase porosity of the hardened cement and cause

a subsequent decrease in strength (Reference 31).

The high rate of hardening of HAC after setting is necessarily accompanied by a rapid development of heat of hydration, although the total heat of hydration per unit weight of cement is about the same as that found in portland cement. Heat liberation of 9 to 15 calories/gram/hour for the initial 8-10 hours is not uncommon and leads to a considerable rise in temperature in the concrete; this temperature development may result in a loss of strength. Increases in temperature due to external causes may produce the same result. As an example, neat cement pastes moist-cured at 77°F then dried for 14 days at the same temperature and a relative humidity of 35 percent, and finally heated to 122-158°F were found to lose 30 to 80 percent of their flexural strength (Reference 33). For one HAC, the flexural strength was reduced from 800 to 150 psi. The autogenous heat-curing of concrete such as would occur in the pseudoadiabatic conditions of Zones 1 and 2 would also create problems. Under adiabatic conditions the temperature rise in a particular concrete was 133°F (Reference 32). Temperature rises of this magnitude are to be expected in the crater repair. The effects of this temperature rise on strength are shown below.

<u>Age, days</u>	<u>Compressive Strength, psi</u>	
	<u>Adiabatic Curing</u>	<u>Curing at 62°F</u>
1	3005	5300
2	1568	4479
3	1680	4623

It has been suggested (Reference 31) that in order to prevent appreciable conversion and hence produce a normal concrete, without strength loss, it is necessary to insure that:

1. The maximum temperature never exceeds 122°F.
2. Temperatures above 100°F are reduced as quickly as possible.
3. The concrete temperature is below 77°F by the end of 24 hours.

These requirements could not be met using the bomb-damage repair concept discussed herein unless the concrete was produced at near-freezing temperatures and placed at near- or below-freezing temperatures. However, the possibility of long-term conversion still would exist.

Regulated-set cement can achieve very early setting times and gain strength very rapidly upon setting. Concrete made with regulated-set cement has been reported to exhibit the same durability performance as concrete made with Type I cement.

The production of regulated-set cement at the cement mill is such that any desired handling time at a given temperature and any early strength gain level, both within reasonable limits, of mortars or concrete made with this cement, can be achieved by manipulating the ingredients in the basic cement clinker. The cement is usually produced to have a handling time of 12-15 minutes at 70°F, and an early strength gain of approximately 1000 psi in reasonably proportioned mixtures. The early strength development begins upon hardening of the cement and is usually complete within 60-90 minutes. Additional strength is then slowly developed with the increasing hydration of the cement. Once a cement is produced for use at a given temperature, e.g. 70°F, its rate of setting will change with deviations from this temperature. Mixture and ambient temperature increases cause the rate to accelerate, while decreases cause it to slow down. The rate of initial strength gain is similarly increased and decreased although the final level does not appear to be significantly altered.

The temperature sensitivity of the cement must be considered when its use is planned for an airfield in a region experiencing wide temperature variations over the seasons. In these instances, it is desirable to specify a cement with the desired strength development and handling times at the average daily temperature of the coolest season of the year. As temperatures warm and handling times shorten, retardation by citric acid additions can then be made to maintain the desired handling times. For a particular cement, actual calibration relations for retarder solution feed rates, related to retarder quantity, versus daily or mixture temperatures can be developed for retarder-adding devices such as the venturi-aspirator pickup described in Section 4.3.2 and Appendix A. Regulated-set concretes have been reported placed at 15°F when the concrete temperature was 35°F and, with no extraneous heat-curing, these still gained an appreciable amount of strength

because the large heat generation of the cement sustained hydration for a sufficient period to get the first early strength level gain before the concrete ultimately froze (Reference 34). This same type of behavior has also been noted for HAC.

Of the above materials, regulated-set cement appears to have the best all-around potential for the repair scheme. Providing temperature curing problems can be resolved, HAC's potential is based on its capability of providing considerably more early strength than does regulated-set cement. It could possibly be used to produce concrete or mortar of considerably more strength than needed, anticipating a loss of strength back to an acceptable level. VHE cement possesses the necessary setting times, develops strength rapidly, and could be an ideal material for rapid repair. More information is needed, however, on its behavior and performance before attempting its use. Fast-Fix cements may have application in repair situations where durability is a minor consideration.

6.3 MATERIALS HANDLING

The major concern in adopting a repair procedure is the amount of material handled. The sand required for the Zones 1 and 2 materials is actually not a problem since only approximately one-third as much sand would have to be stockpiled and transported to the repair of three major craters as opposed to the 2000 yd³ of select fill presently required for repair (Reference 6). The water supply is also not a major problem if the suggested approach of using impoundments adjacent to runways is followed (Section 4.1). If the water must be delivered by truck, the problem becomes more complex due to the limited volume, off-road limitations, and refilling times of such trucks. The storage and handling of the cement are perhaps the most difficult of the materials handling problems. From the handling and storage techniques for cement described in Section 4.2, the use of rubberized bags specifically designed for rapid unloading appears to be the most practicable and economical. The mobile field storage units are the most efficient for this application but are expensive and, depending on the extent of damage to the runway and surrounding area, may be difficult to move

into position when fully loaded. The rubberized bags can be sized for ease of handling by equipment in the rapid repair kit equipment package. These bags can be readily deployed around the airfield and may even be placed in underground bunkers, if desired. The cement can, in theory, be stored in these air- and watertight bags indefinitely without experiencing any degradation in performance. Concerns about storage always arise; however, these can be alleviated by integrating the cement into normal base concreting operations on an immediate replacement basis, thereby providing a continual turnover of the cement in storage.

Foaming agent concentrates are generally available in 55-gallon steel drums and thus can be handled and stored as such. Citric acid is generally available in paper bags. These can be sized to optimize batching and handling requirements. If the bags do not provide adequate storage protection, they can be replaced with special plastic bags, fiber drums, or steel drums.

6.4 EQUIPMENT REQUIREMENTS

The equipment required to implement the regulated-set repair scheme should not precipitate major fund expenditures for equipment development. Other than the batching and pumping units including the foam generator and the mobile field cement storage tanks, if used, every other piece of equipment needed is already available in Army and Air Force inventories with most of it already included in existing BDR equipment kits. Some modifications of vehicular equipment requirements for the repair concept are included in Section 6.1. The batching and pumping units are presently available from a number of U. S. manufacturers although their capacities are somewhat less than needed for the rapid repair scheme. Most of these manufacturers have revealed that the capacities of the present units have been tailored to the needs of the construction industry and that upgrading them to meet the requirements of the specifications discussed in Appendix A is not a difficult problem although it would require some additional design engineering. Mobile field cement storage tanks of the capacities discussed in Section 4.2 are presently commercially available.

TABLE 6.1 PROPOSED BOMB-DAMAGE REPAIR TEAM

Repair Team	Personnel Required	
	Per Crater	Total
Overall Repair Supervision:		
Supervisor	--	1
Assistant supervisor	--	1
Runway Cleaning Crew:		
Sweeper operators	--	5
Front-end loader operator	--	1
Hauling Crew:		
Supervisor	--	1
Front-end loader operator	--	1
Dump truck operator	--	10
Mobile crane operator	1	4
Mobile crane helper	1	4
Tractor trailer operator	--	3
Crater Repair Crew:		
Supervisor	1	3
Front-end loader operator	2	6
Dozer operator	1	3
Pumping equipment operator	3	9
Pumping equipment helper	3	9
Materials delivery systems helper	3	9
Crater helpers	6	18
New Centerline Crew	--	4
Total	--	92

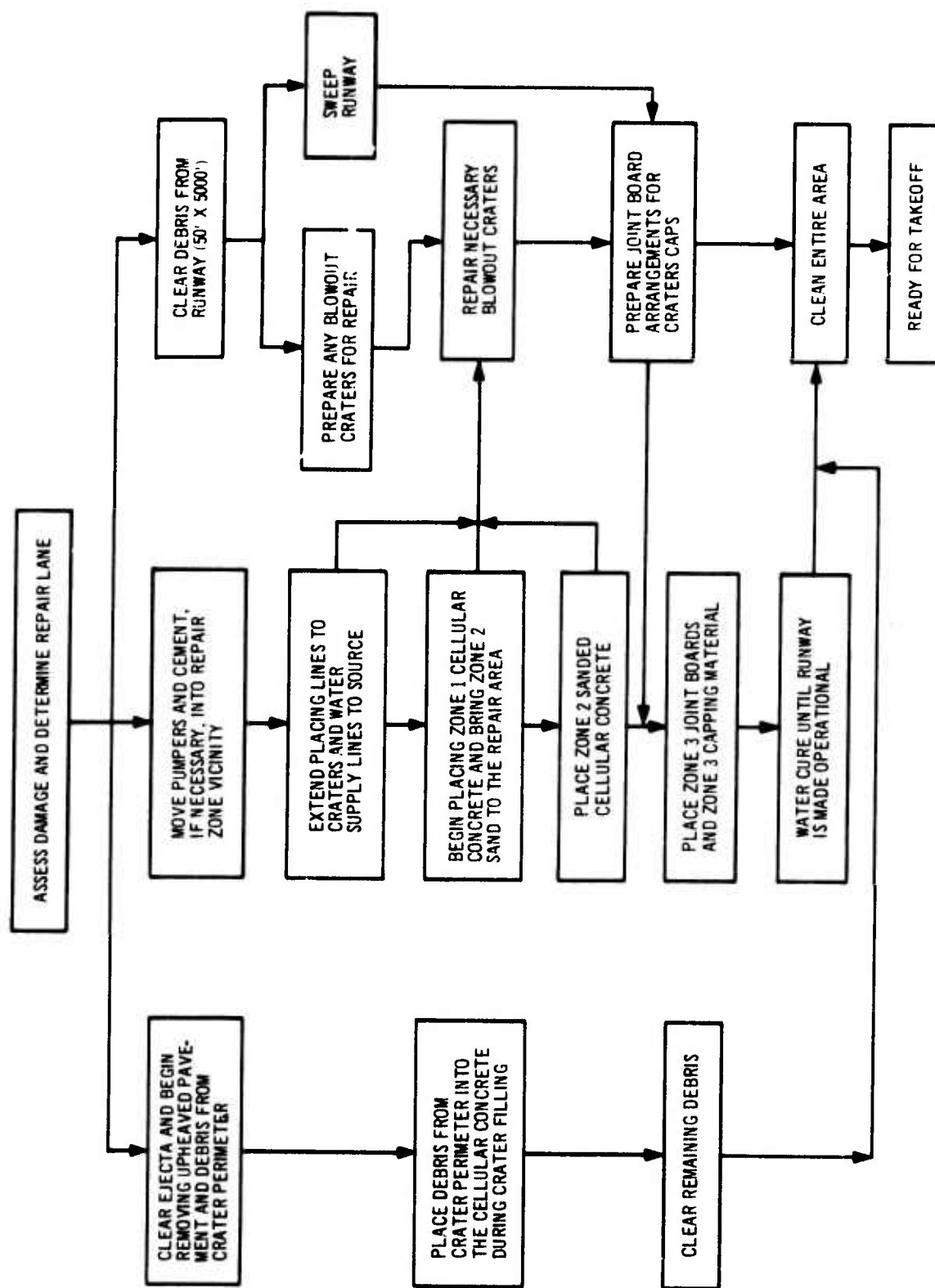


Figure 6.1 Regulated-set cement system repair flow diagram

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

The responsibility for immediate emergency damage recovery for Air Force pavement facilities is detailed in AR 415-30 and AFR 88-12 and is assigned to the Air Force which presently uses the procedures described in AFM 93-3 (Reference 6) to accomplish this mission. This report presented another concept for the rapid repair of bomb-damaged runways, i.e. the use of regulated-set cement as a rapid-repair material. The regulated-set cement repair concept was developed in an attempt to overcome shortcomings in the present procedure and to provide flexibility and permanence to emergency repairs. The various features of this concept have been explored and some of them evaluated experimentally. However, the entire concept has not been evaluated in a full-scale repair; therefore it remains a concept and not a recommended practice. Technically, the concept is well within the current state of technology, but additional work will be necessary to validate the scheme and to make a relative evaluation to determine its real potential.

The regulated-set cement repair scheme has the potential to satisfy the present criteria of repairing, in 4 hours time, a runway 50 by 5000 feet crossing three craters formed by 750-pound bombs exploding below the surface of the runway, although the actual repair of a full-size crater has not yet been attempted. These runways would be at tactical airfields where the wheel loading by aircraft would be comparable to that of the F-4E and F-111 aircraft. The equipment and procedures needed for the full-scale procedure have been successfully applied to the repair of smaller craters, thereby demonstrating the flexibility of the scheme for repairing everything from potholes to full-size craters. These various size craters can be repaired either separately or concurrently with the large crater repairs. The repair concept can also be applied to all craters in the airfield after the emergency repairs are made, thereby providing Base Engineering with an additional capability.

The regulated-set cement materials can be pumped several hundred feet into the crater working area, thereby allowing the repair equipment to be set up out of the area immediately surrounding the crater. This minimizes crater cleanup interference and, by simply moving the placing lines, provides a capability of repairing more than one area at a time without moving and setting up the batching and pumping equipment. Many small craters could be repaired by one unit from this central location.

In the regulated-set cement repair scheme, the resulting repaired surface is level with the surrounding pavement, thereby eliminating the problems of ramp-up and anchorage encountered with matting repairs. The regulated-set cement mortar capping material could possibly be used as a seating material into which matting could be placed, level with the pavement surface, to provide a matting wearing surface.

The repairs made with the regulated-set cement are permanent and should not have to be upgraded or removed and replaced at later dates, unless the airfield begins to handle aircraft whose wheel loadings are more severe than those of the F-4E and F-111 aircraft. The repair should have the same durability characteristics as any Type I portland cement concrete.

Implementation of the regulated-set repair scheme reduces the manpower requirements approximately 25 percent from that required in the present procedure. The actual number of personnel required will depend on the method used for cement storage and handling. All personnel assignments involved in the repair require no higher skill levels than presently required in the AFM 93-3 BDR repair. Batching and pumping equipment should be operated by trained personnel. This operation is extremely simple, however, and should not require more than one day of training combined with routine state-of-readiness training to produce the necessary trained personnel.

Present BDR vehicle and construction equipment kits would have to be modified to include the batching and pumping equipment plus supporting appurtenances. An accompanying deletion of that equipment, mostly dump trucks and compaction equipment, presently in the kits that will not be needed for the new procedure must also be made. No new equipment

development is foreseen. All recommended equipment is either already in military inventories or is commercially available. Some upgrading of capacities in the available standard batching and pumping units using the foam generators may be needed to satisfy the volume and time constraints of the repair procedure.

Regulated-set cement appears to be a suitable cementing material for the type repair proposed. It has controllable setting times and adequate strength development for the repair requirements. Other cements, such as VHE cement, may also prove satisfactory for this type of repair. Availability of regulated-set cement is presently limited to one producer in the U. S. but its availability is rapidly growing in Europe and Japan. Storage and handling of the cement, a major concern of personnel not familiar with major construction, is a topic often raised in discussions of repairs of this type. While it appears to be a formidable undertaking, it is in practice no more difficult than moving any bulk material, such as the select-fill hauling required in the present repair procedure. Air- and watertight containers for storage, handling, and transportation of cement are commercially available. Consideration should be given to integrating the regulated-set cement into normal base construction operations to provide turnover of stored cement, to provide familiarity of use to base personnel, and to take advantage of the high early-strength characteristics of the cement in base construction operations.

Water supply systems for the repair can be developed to be multi-purpose such as for runway fire fighting, storm water runoff control, and recreational use.

Cellular concrete can be proportioned to provide a more than adequate base course strength in 2 hours time for rigid pavements subjected to the wheel loadings of F-4E and F-111A aircraft. Regulated-set cement mortar used as a capping material can provide the necessary early age flexural strength for these loadings. The capping material must include aggregate of some type to reduce the problem of drying shrinkage at later dates. Joint boards should be included in the construction of the large crater cap to facilitate both ease of placement and finishing and also

to provide crack control in the wearing surface. Additional development of finishing techniques for the capping material is needed.

7.2 RECOMMENDATIONS

Based on the apparent potential of the regulated-set cement repair concept for repairing bomb craters of all sizes and shapes up to those formed by 750-pound bombs exploding beneath the runway, it is recommended that the concept be evaluated on a full-scale prototype crater using the equipment, materials, and personnel described in this report. Prior to this evaluation, some additional development work relating to methods of placement of debris into the cellular concrete fill, methods of joint board assembly and placement, and screeding and final preparation of the capping material should be undertaken. Coincidental with the prototype evaluation, an entire program for implementation of the repair method on a chosen airfield should be developed and evaluated with respect to present repair procedures.

Load tests of the proposed repair should be conducted at WES using the WES load carts for the F-4E and F-111A wheel loadings to establish acceptable criteria for the cellular concrete subgrade and the regulated-set cement pavement thickness needed for such subgrades. Other details such as tie-in of the repair to existing pavements should also be studied.

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APPENDIX A

SAMPLE SPECIFICATION FOR A SELF-CONTAINED, PORTABLE
CELLULAR (FOAM) CONCRETE MIXER AND PLACING UNIT

SECTION ____ - DESCRIPTION/SPECIFICATIONS

____.1 WORK TO BE DONE. The work to be done under these specifications consists in furnishing and delivering to the _____

(Organization and Location)

the items and/or services listed in the Schedule, in accordance with the following specifications and all other provisions of this solicitation including any drawings attached.

____.2 GUARANTEE. The manufacturer's standard warranty applicable to the type item being procured hereunder will apply.

____.3 GENERAL. These specifications describe a self-contained, portable concrete mixer, designed and constructed for field production of cellular (foam) concrete and hereinafter referred to as "the unit." It shall mix a cement and water slurry or a cement, sand, and water mortar with preformed foam in the proper proportions to provide cellular concrete at controlled densities and at controlled outputs.

____.4 COMPONENTS. The unit shall include but not be limited to the following components, properly sized and installed complete as part of the unit so that the components and the unit shall meet the performance requirements specified herein.

____.4.1 A gasoline or diesel engine shall furnish all power required for operating the unit under any and all of the conditions specified below for continuous-duty periods of 8 hours or longer. A fuel tank shall be provided large enough for the 8 hours of operation without refueling. (The 8-hour requirement may be too restrictive and can be adjusted downward, depending on anticipated requirements and refueling capabilities.)

____.4.2 The contractor may use any types of power conversion

equipment to accomplish the requirements specified. These may include manual or hydramatic shift transmissions, hydraulic pumps and motors, air motors, electric generators and motors, etc. All components, however, shall be powered primarily from the engine specified in ____4.1.

____.4.3 An air compressor if required shall provide the proper pressure and quantity of compressed air for operation as specified.

____.4.4 A water pump shall be installed to provide the required water pressure for operation. It shall be capable of pumping water supplied to it at static pressures as low as 2 psig. Piping and valving shall be arranged so that wash and cleanup water is available from a faucet and from within each mixer. The water pipe providing water to the mixer shall contain a properly sized venturi aspirator for admixture pickup if required.

.4.5 Slurry Mixer.

____.4.5.1 The Government will provide bulk portland cement and fine aggregate (sand) to points immediately adjacent to the unit.

____.4.5.2 A manually adjustable cement conveyor shall convey the cement from the bulk storage facility provided by the Government to the slurry mixer. The flow of cement into the slurry mixer shall be adjustable to provide a range of 0 to 1900 pounds of cement per minute.

____.4.5.3 One or two manually adjustable fine aggregate (sand) conveyors, operating either singularly or together, shall convey the fine aggregate from the fine aggregate facility provided by the Government to the slurry mixer. The capacity(s) of the conveyor(s) shall be such that the range of the rate of flow of fine aggregate into the slurry mixer shall be from 0 to 4000 ppm. This rate can be achieved by either one conveyor or by two conveyors operating together.

____.4.5.4 The mixer shall be of such construction that the slurry produced is free of lumps. Dwell time of slurry or mortar in the mixer shall be between 30 and 90 seconds.

____.4.5.5 The output of slurry or mortar by volume shall be adjustable over the required range.

____.4.5.6 Controls for the proper feed of cement, sand, and water may be manually selectable to provide water/cement ratios including

but not limited to 0.40 to 1.0 by weight, sand/cement ratios including but not limited to 1.5 to 3.5 by weight, and the densities and outputs of foamed concrete and mortar specified in _____.6 below.

____.4.6 Preformed Foam Generator.

____.4.6.1 A liquid foam concentrate delivery system shall convey the required amounts of liquid concentrate from a drum on ground level and supply it to the foaming unit or to a container which in turn feeds the foaming unit.

____.4.6.2 Compressed air, if required, and water shall be added to the foaming unit as selected.

____.4.6.3 Volume flow rates of air, water, and liquid foam concentrate shall be adjustable and manually selectable to provide the densities and outputs specified in _____.6 below.

____.4.7 The foam-slurry or foam-mortar blending system shall be capable of receiving the slurry or mortar and preformed foam and blending the two components into a uniform product hereafter called cellular concrete ready for delivery by pumping to the use site. Blender output shall be variable within the limits specified in _____.6.

____.4.8 Cellular concrete pump shall be capable of continuously delivering the cellular concrete at the densities and outputs specified in _____.6 through a 4-inch Government-furnished flexible hose for horizontal distances up to but not limited to 500 feet with no vertical lift. Fitting for connecting 4-inch hose shall be installed at the discharge of the unit.

____.5 CONSTRUCTION.

____.5.1 All components shall be mounted on a single trailer suitable for towing over two-lane U. S. highways. Overall dimensions of the unit shall not exceed 8 feet wide, 35 feet long, or 12 feet high.

____.5.2 The trailer shall be equipped with all safety features required by Interstate Commerce Commission and the Federal Motor Vehicle Safety Standards and Regulations including but not limited to brakes; chassis; running, stop, and turn lights; properly sized axles; and type and construction of trailer hitch.

____.5.3 The trailer shall be equipped with screw type leveling

lacks at all corners for leveling and stabilizing for operation.

____.5.4 All components that have need for indicating instruments (for operation within their standard warranty requirements) shall have them mounted within view of the operator.

____.5.5 The trailer shall be equipped with a trailer hitch properly located and installed for towing the trailer with all the equipment installed.

____.5.6 The unit shall have all tubing, piping, valves, fittings, electrical wiring, motors, regulators, and any other equipment needed for operation as specified herein properly installed; and with all valve handles, switches, and other control or adjustment devices mounted within access of the operator.

____.5.7 The completed unit shall be painted with the manufacturer's standard paint application.

____.6 PERFORMANCE. The unit shall deliver, meter, mix, blend, and pump the previously specified components to form cellular concrete and deliver it continuously to the point of use 500 feet from the unit at an adjustable rate including but not limited to 50 to 80 yd³/hr for all densities specified below. Cellular concrete made without fine aggregate (sand) or mineral fillers shall have output densities adjustable throughout the range from but not limited to 30 to 70 pcf at the specified water/cement ratio (see _____.4.5.6). Cellular concrete made with fine aggregate (sand) shall have output densities adjustable throughout the range from 50 pcf up to that density produced at the specified water/cement ratio (see Section _____.4.5) when no pre-formed foam is added. All densities of cellular concrete shall be controlled within a tolerance of ± 5 percent under steady operating conditions. The unit shall be capable of the above specified performance while operating in rainy weather and at 0 to 110°F ambient air temperature.

____.7 SERVICES OF FACTORY REPRESENTATIVE. Within five calendar days after receipt of the unit at the _____, the contractor shall furnish the services of a factory representative, cognizant of the unit design and details, to

start up and check out the unit and provide informal operational and maintenance instructions to operating engineers and technicians. The period of this instruction shall be at least 8 hours between 8:00 a.m. and 4:30 p.m. The contractor will be responsible for demonstrating unit performance and compliance with technical specifications at the time of initial checkout. Payment of the contract amount will constitute full and final payment for the unit and all services incidental to the furnishing, delivering, instructing, final adjustment, checkout, and operation for acceptance purposes.

____.8 MANUALS. The contractor shall furnish with or before delivery of the equipment two sets of operation and maintenance manuals.

APPENDIX B

NOTATION

The principal symbols used in this report are listed below. Special-purpose subscripts and symbols are not listed but are explained in the text.

CBR	California Bearing Ratio
d	Density
g	Aggregate content
h	Pavement thickness, inches
k_1	Water/cement ratio
k_2	Sand/cement ratio
L	Single wheel load, pounds
P	Tire pressure, psi
S	Shrinkage
So	Shrinkage of neat paste
V	Volume
W	Weight, lb
α	Exponent
γ	Unit weight of water (62.3 pcf)
ρ	Specific gravity
σ	Flexural strength, psi

In accordance with ER 70-2-3, paragraph 6c(1)(b), dated 15 February 1973, a facsimile catalog card in Library of Congress format is reproduced below.

Hoff, George C

A concept for rapid repair of bomb-damaged runways using regulated-set cement, by George C. Hoff. Vicksburg, U. S. Army Engineer Waterways Experiment Station, 1975.

159 p. illus. 27 cm. (U. S. Waterways Experiment Station. Technical report C-75-2)

Sponsored by Air Force Weapons Laboratory, Air Force Systems Command, Kirtland Air Force Base, NM.

Prepared for Office, Chief of Engineers, U. S. Army, Washington, D. C., under RDTE Project 4A762719AT31, Task 002, Work Unit 005.

References: p.151-153.

1. Bomb craters. 2. Bomb damage. 3. Cements. 4. Regulated-set cements. 5. Runway repairs. 6. Runways. I. Air Force Weapons Laboratory, Kirtland Air Force Base, N. M. II. U. S. Army. Corps of Engineers. (Series: U. S. Waterways Experiment Station, Vicksburg, Miss. Technical report C-75-2)

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