U. S. DEPARTMENT OF COMMERCE

BUILDING MATERIALS AND STRUCTURES

REPORT BMS78

Structural, Heat-Transfer, and Water-Permeability Properties of Five Earth-Wall Constructions

by

HERBERT L. WHITTEMORE,
AMBROSE H. STANG,
ELBERT HUBBELL, *and*
RICHARD S. DILL

NATIONAL BUREAU OF STANDARDS

The program of research on building materials and structures carried on by the National Bureau of Standards was undertaken with the assistance of the Central Housing Committee, an informal organization of governmental agencies concerned with housing construction and finance, which is cooperating in the investigations through a committee of principal technicians.

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UNITED STATES DEPARTMENT OF COMMERCE · Jesse H. Jones, Secretary
NATIONAL BUREAU OF STANDARDS · Lyman J. Briggs, Director

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ISSUED OCTOBER 1, 1941

The National Bureau of Standards is a fact-finding organization; it does not "approve" any particular material or method of construction. The technical findings in this series of reports are to be construed accordingly.

UNITED STATES GOVERNMENT PRINTING OFFICE · WASHINGTON · 1941
FOR SALE BY THE SUPERINTENDENT OF DOCUMENTS, WASHINGTON, D. C. · PRICE 20 CENTS

Foreword

Interest has been expressed from time to time in the use of earth as a building material for the construction of houses as evidenced by numerous articles in popular periodicals, and a considerable number of houses have been built of this material. There has, however, been a lack of technical information on the structural, thermal, and water-permeability properties of such constructions.

In order that no material be overlooked which might contribute to the development of low-cost housing, specimens of earth walls as described in this report were constructed in cooperation with The Office of Indian Affairs and the National Youth Administration. The structural, heat-transfer, and water-permeability properties were determined by methods simulating conditions to which the walls would be subjected in actual service. The same methods have previously been used to determine the properties of masonry and wood constructions (BMS5, BMS7, BMS25).

The National Bureau of Standards does not "approve" a construction, nor does it express an opinion as to its merits for reasons given in reports BMS1 and BMS2. The technical facts presented in this series provide the basic data from which architects and engineers can determine whether a construction will meet definite performance requirements.

This report is not to be construed as a general indorsement of earth constructions; it aims to present the technical information without regard to whether the results are advantageous or disadvantageous. Because of the special nature of this building material, there has been included in this report general information on methods of design and construction prepared by the group of consultants referred to in the report. The National Bureau of Standards has had no actual experience in the construction of earth houses and has no information on the subject for distribution other than that contained in this report.

Lyman J. Briggs, *Director.*

Errata to accompany National Bureau of Standards Building Materials and Structures Report BMS78, Structural, Heat-Transfer, and Water-Permeability Properties of Five Earth-Wall Constructions

Page 10, left column, after second line insert:

> "The proportion of cement was 8 percent by weight of dry-earth mixture, approximately 6.5 percent by damp weight."

Page 21-22, delete paragrpah reading:

> "Unless stated otherwise, the compressive load was applied to the inside face (the face nearer the load line)."

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ABSTRACT

For the program on the investigation of low-cost house constructions, specimens representing adobe, bitudobe, monolithic terracrete, terracrete-block, and rammed-earth walls were constructed with the cooperation of The Office of Indian Affairs and the National Youth Administration. These specimens were subjected to structural, heat-transfer, and water-permeability tests.

Sixty structural specimens were subjected to compressive, transverse, concentrated, impact, and racking loads. The transverse, concentrated, and impact loads were applied to once face. The loads simulated those to which elements of a house are subjected in actual service.

The deformations under load and the sets after the load was removed were measured for each increment of load.

Five heat-transfer specimens were subjected to a temperature differential that might occur in actual service.

Five water-permeability specimens were tested under conditions that simulated exposure to a heavy, wind-driven rain.

I. INTRODUCTION

The use of earth for construction arose from the necessity of utilizing materials at hand in a simple and direct manner. Buildings were constructed of earth by the Indian peoples of the Southwest, who made crude adobe block and developed methods of construction and a type of architecture particularly suited to their needs. With the arrival of the Spaniards, the use of adobe became more general. Later rammed-earth structures appeared along the Atlantic Coast, and still later sod houses were built on the plains of the Midwest by the pioneer homesteaders.

The possibility that earth walls might contribute to the solution of the low-cost housing problem led the Bureau to include this type of construction in the BMS program on low cost house constructions. Although articles appearing from time to time in popular periodicals have pointed out advantages of earth walls for houses, there is a definite need for technical information on the structural, thermal, and water-permeability properties of such constructions.

Thomas Hibben, who built rammed-earth houses in Birmingham, Ala., under the Farm Security Administration, offered to build test specimens with the aid of the District of Columbia National Youth Administration. The Office of Indian Affairs cooperated by assigning Elbert Hubbell, instructor of rammed earth, to supervise the construction of the specimens.

To outline a program on earth walls, experts in the Federal Service and elsewhere were invited to a conference at the National Bureau of Standards on January 3, 1940. Attending this conference were:

Thomas Hibben, National Youth Administration.
Elbert Hubbell, The Office of Indian Affairs.
Comdr. C. S. Stephenson, Bureau of Medicine and Surgery, Navy Department.
T. A. H. Miller, Bureau of Agricultural Chemistry and Engineering.
Francis Macdonald, Consulting engineer.
D. E. Parsons, National Bureau of Standards.
C. C. Fishburn, National Bureau of Standards.
H. L. Whittemore, National Bureau of Standards.
A. H. Stang, National Bureau of Standards.
G. W. Shaw, National Bureau of Standards.

Comdr. C. S. Stephenson (MC), U. S. Navy, when a consultant in the Health Safety Division of the Tennessee Valley Authority, recommended rammed-earth houses as an economical means of improving health conditions of the people of the Tennessee Valley.

T. A. H. Miller made available for this study extensive data on earth buildings, based on surveys covering a period of years.

Francis Macdonald has erected rammed-earth houses and has investigated the properties of mixtures of earth and portland cement. His handbook, "Terracrete," describes procedures for constructing houses of this material.

All these experts served as consultants, cooperating in the planning of the program, the conduct of the tests, and the preparation of the report.

In addition to those present at the conference, Wallace Ashby, U. S. Department of Agriculture, who has been actively interested in the possibilities and development of earth constructions, particularly weather-resistant coatings, contributed valuable comments and suggestions. Albert L. Miller, Director of the District of Columbia National Youth Administration, furnished educational-project workers to assist in building the specimens.

Many earth constructions were considered at the conference. Those selected for this program—adobe, bitudobe, monolithic terracrete, terracrete block, and rammed earth—represented the earth constructions which have been used for houses.

The earth used was a mixture containing 50 percent of clay loam and 50 percent of sand-gravel with moisture content between 10 and 12 percent. Analysis of the mixture showed it to consist of 42 percent fine sand, 19 percent coarse sand, 22 percent silt, 17 percent clay, and 8 percent colloids.

Three kinds of tests were applied to specimens of each type of construction: structural, heat transfer, and water permeability. For the structural tests, specimens were subjected to compressive, transverse, concentrated, impact, and racking loads, all simulating the loads which walls of an occupied house encounter in actual use.

The deflection and set under each increment of load were measured because the suitability of a wall construction depends not only on its resistance to deformation when loads are applied, but also on its ability to return to its original size and shape when the loads are removed.

The weights of all five constructions were nearly the same, ranging from 120 lb/ft^3 for the bitudobe to 137 lb/ft^3 for the terracrete block. The monolithic terracrete and rammed-earth walls were 14 in. thick, the block walls approximately 12 in. thick. The adobe, bitudobe, and rammed-earth walls carried compressive loads up to 100 lb/in.^{2}; the terracrete walls were much stronger, carrying compressive loads up to 800 lb/in.^{2}, both under eccentric loading. All of the walls withstood transverse loads, such as are produced by the wind, of 54 lb/ft^2 or more. The performance under impact was better than that of many types of masonry walls, and like masonry walls the earth walls resisted concentrated loads extremely well, except near sharp corners. The racking strengths of the adobe, bitudobe, and rammed-earth walls were of the order of 2,000 to 3,000 lb/ft, while those of the terracrete walls were greater than 6,250 lb/ft. These values may be compared with 2,000 lb/ft for conventional frame construction, and 3,000 to 4,000 lb/ft for tile or cement-block construction.

From the point of view of the structural properties, all five forms of earth construction are quite satisfactory for one- and two-story houses, provided the work is done by persons who have had some training and the composition and moisture content of the earth used are controlled within suitable limits.

For the heat-transfer tests, specimens were subjected to a temperature differential that is often found in the Northern United States. The rate of transfer through earth walls is about the same as that through ordinary concrete walls of the same thickness. It is probable that the heat transfer depends on very many variables, but the results at present available indicate no great insulating value for 12- and 14-in. earth walls as compared with ordinary uninsulated walls. Earth walls have high heat capacity, which aids in reducing fluctuations of temperature and in maintaining a more uniform temperature. In summer, the temperature inside an earth house does not rise to as high values as houses having walls of lower heat capacity, but the average temperature over a long time is not affected. Earth walls are, of course, fireproof.

For the water-permeability tests the exposed face of a specimen was subjected to a thin film of running water and an air pressure of 10 lb/ft^2 above atmospheric. The amount of water applied was about 15 gal per hr per linear ft of wall.

Earth walls must be protected against the erosion of driving rains. In the water-permeability test, an unprotected rammed-earth wall was worn away to a depth of ½ in. in 40 min. Water did not penetrate the wall in this time. The unprotected terracrete walls were considerably better as regards erosion. The block walls were quickly penetrated through the mortar joints. Plain adobe was eroded to a depth of 1¾ in. in 40 min of exposure. The Bureau has made no special study of protective coatings for earth walls, but a large amount of work has been done at the Agricultural Experiment Station of South Dakota State College. In many climates, protection can be secured by using an overhang on the roof.

Members of the staff of the National Bureau of Standards have had no personal experience in the construction of complete houses of earth. Some instruction is required and the moisture must be held within definite limits. The following sections II to VI, inclusive, give the technical details of the tests and the results.

Section VII presents an account of the various types of earth construction which have been used; a discussion of the selection of earth; methods of construction, including typical details; and methods of protection against the harmful effects of moisture. This section is based on information supplied by the group of consultants previously mentioned.

II. MATERIALS

1. Earth

A preliminary investigation indicated that a mixture of clay loam and sand-gravel, 50 percent of each by loose volume, would be suitable for all test constructions. This mixture is designated "earth" in this report.

Clay loam and sand-gravel were obtained from the Washington National Airport, south of Washington, D. C.

The sieve analysis of the clay loam, sand-gravel, and earth is given in table 1; the hydrometer analysis in table 2; and the physical constants in table 3. The hydrometer analyses and the physical constants were determined by the Public Roads Administration in accordance with Standard Specifications for Highway Material and Methods of Sampling and Testing (1938) of the American Association of State Highway Officials.

TABLE 1.—*Sieve analysis of the earth*

U. S. Standard Sieve	Passing, by weight		
	Clay loam	Sand-gravel	Earth
	Percent	*Percent*	*Percent*
½ in	100	100	100
⅜ in	99	99	100
No. 4	98	79	92
No. 10	98	59	84
No. 40	96	39	68
No. 140	76	6	41
No. 200	68	5	36

TABLE 2.—*Hydrometer analysis of the earth*

Particle size	Distribution, by weight		
	Clay loam	Sand-gravel	Earth
Sand:	*Percent*	*Percent*	*Percent*
2 to 0.42 mm	2	43	19
0.42 to 0.05 mm	37	49	42
Silt	33	4	22
Clay	28	4	17
Colloids	16	1	8

TABLE 3.—*Physical constants of the earth*

[Material passing U. S. Standard Sieve No. 40]

Physical constant	Values [a]		
	Clay loam	Sand-gravel	Earth
	No.	*No.*	*No.*
Liquid limit	29		22
Plasticity index	10	NP [b]	5
Shrinkage limit	16.0		14.9
Shrinkage ratio	1.8		1.9
Centrifuge moisture equivalent	21		17
Field moisture equivalent	19		18

[a] Standard Specification for Highway Materials and Methods of Sampling and Testing (1938) of the American Association of State Highway Officials.

[b] NP, nonplastic.

2. Cement

The cement was Medusa Cement Co. "Medusa" brand portland cement donated by the Portland Cement Association, Chicago, Ill. The cement complied with Federal Specification SS–C–191a for soundness, fineness, time of set, and tensile strength.

3. Lime

The lime was lime putty made by slaking Standard Lime & Stone Co. "Washington" brand powdered quicklime. The putty contained 40 to 45 percent dry hydrate by weight.

4. Sand

The sand for mortar was Potomac River building sand. The sieve analysis is given in table 4.

TABLE 4.—*Sieve analysis of sand in mortar for adobe, bitudobe, and terracrete-block walls*

U. S. Standard Sieve No.	Passing, by weight
	Percent
8	100
16	88
30	53
50	11
100	2

5. Mortar

The mortar proportions were, by weight, 1 part of portland cement, 0.43 part of hydrated lime, and 5.1 parts of dry sand; by volume, 1 part of portland cement, 1 part of hydrated line, and 6 parts of loose, damp sand, assuming that cement weighs 94 lb/ft^3 and dry hydrated lime 40 lb/ft^3 and that 80 lb of dry sand is equivalent to 1 ft^3 of loose, damp sand. The materials for each batch were measured by weight and mixed for not less than 2 min. in a batch mixer having a capacity of ⅔ ft^3. The amount of water added was adjusted to the satisfaction of the mason.

A sample of the mortar was taken for each wall specimen, the flow and the water retention were determined in accordance with Federal Specification SS–C–181b, and six 2-in. cubes were made. Three cubes were stored in water at 70°F and three in air near the wall. The compressive strength of each cube was determined on the day the corresponding wall specimen was tested. The physical properties of the mortar are given in table 5.

TABLE 5.—*Physical properties of mortar for adobe, bitudobe, and terracrete-block walls*

Type of wall	Structural symbol	Average moisture content	Consistency as used [a]	Water retention [a]	Compressive strength [b]	
					Air storage	Water storage
		Percent	*Percent*	*Percent*	*lb/in.²*	*lb/in.²*
Adobe	*DB*	22	100	80	610	970
Bitudobe	*DC*	21	91	78	860	1,120
Terracrete block	*DE*	21	108	80	710	950
Average		21	100	79	730	1,010

[a] Determined in accordance with Federal Specification SS–C–181b.
[b] Determined on the day the corresponding wall specimen was tested (age 28 days).

6. Bituminous Stabilizer

The American Bitumuls Co., Baltimore, Md., cooperated by donating the bituminous stabilizer, by determining the earth and stabilizer proportions, and by supplying photographs for figures 70, 71, and 72. K. N. Cundall and W. K. Smith assisted in making bitudobe block by commercial-production methods.

The properties of the stabilizer, determined by the Paint Section of the National Bureau of Standards, are given in table 6.

TABLE 6.—*Properties of bituminous stabilizer*

Property		Value
Viscosity	seconds	73
Miscibility		Satisfactory
Demulsibility	percent	0.1
Mixing test	do	.2
Dehydration at 100° F	do	.74
Residue at 163° C	do	59

The viscosity, miscibility with water, and demulsibility were determined according to ASTM D244–34T, Methods of Testing Emulsified Asphalt. The mixing test, dehydration at 100° F, and residue at 163° C were made in accordance with Bureau of Yards and Docks, Navy Department, Specification 8983. American Bitumuls Co., "Bitumuls."

III. SPECIMENS

The test specimens were built at the National Bureau of Standards with the cooperation of The Office of Indian Affairs and the National Youth Administration. The same "earth," with or without admixtures of portland cement or emulsified asphalt, was used in all five types of construction selected for this study. The range of moisture, proportions of admixture, and test results given in this report apply to this particular earth only.

1. Adobe-Block Walls

(*a*) *General Information*

Of the five types, the adobe-block wall is the one most widely known in the United States. Adobe block constitute a reliable building material in the Southwest, where the arid climate is favorable to their use. Adobe construction is common around Las Cruces, N. Mex., but even in that area some form of exterior covering is necessary for permanent structures.

Although it is customary to make the block from suitable earth located adjacent to the building site, some communities take all the earth needed for this purpose from a single pit of satisfactory material. For adobe-block manufacture the earth should have a not too high clay content, should be easily molded when mixed to the proper consistency, should dry without appreciable cracking or warping, and should produce brick of a strength sufficient for the structural needs of the wall in which it is to be used. Straw mixed with the earth may reduce excessive cracking.

To mix adobe satisfactorily, a method that will pulverize the earth and distribute the water uniformly is essential.

The earths used in adobe construction should not be confused with the heavy clays and silty loams sometimes termed "adobe."

(b) *Manufacture of Block*

For the block used in these tests the adobe mixture was agitated for 3 min. in a rotating-drum concrete mixer (capacity 6 ft^3) shown in figure 1, then placed in the molds shown in figure 2. The molds were made of yellow pine $^{25}/_{32}$ by 5 in., S4S (surfaced four sides). The moisture content of the mixture was from 16 to 20 percent of the weight of the dry earth. To provide a rough surface and to facilitate the drying of the block, the molds were placed on carpet or burlap. Three full-sized blocks were molded simultaneously in one mold and four half-sized blocks in another mold.

The adobe was thoroughly kneaded in the mold, especially at the corners. Insufficient kneading resulted in cavities in the lower surface of the block. To reduce cracking, the upper surface of the block was smoothed flush with the mold, as shown in figure 3. Upon removal of the mold, the upper surface of the block was concave (to about $^5/_{16}$ in.) as shown in figures 3 and 4.

When the blocks could be handled without breaking, they were turned on edge to hasten drying. The dry blocks were stacked as shown in figure 5.

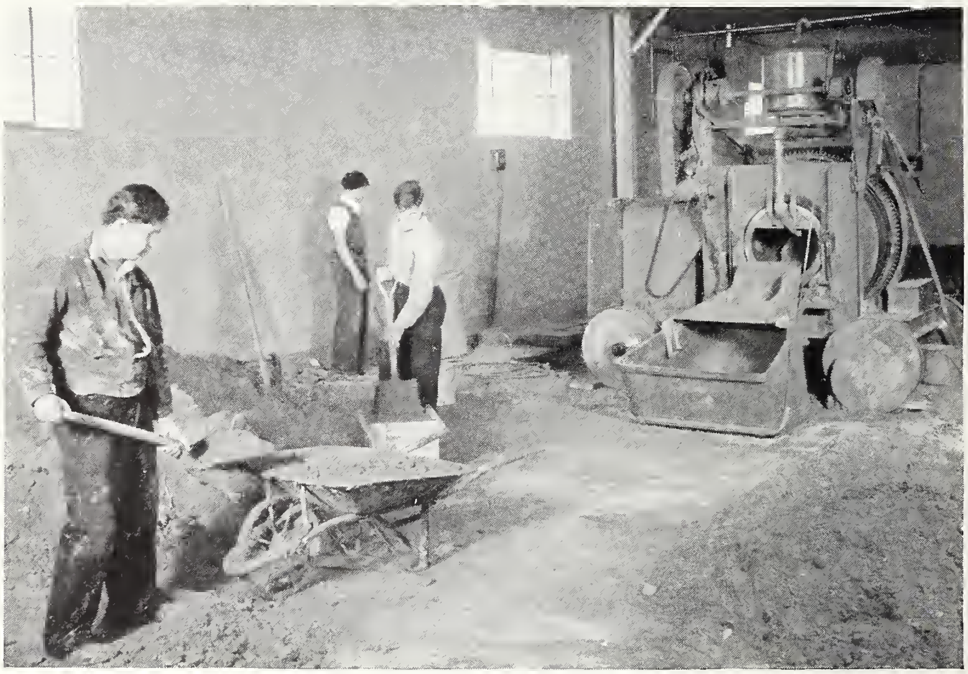

Figure 1.—*Production of adobe mixture.*

(c) *Control*

The essential control for adobe block is the total moisture of the mixture. The allowable limits are from 16 to 20 percent, by dry weight. If the moisture is less than 16 percent, the mixture will be too stiff and will adhere to the form; lifting the form off will make the upper surface of the block excessively concave and will crack the lower surface. If the moisture is greater than 20 percent, the mixture will be too thin, and the block will slump excessively when the form is removed; also there will be shrinkage cracks in the dried block.

(d) *Construction of Wall*

The specimens were built on structural steel channels. The bed joints were formed by depositing only enough mortar for one block at a time and were built up higher near the wall faces than at the center. The cupped faces of the block were laid down and the plane faces, bottom of the block as cast, were laid up, as shown in figure 6. The block were moved into alinement after placing on the mortar beds, but not much pressure could be applied on the top surfaces without breaking them. Bearing of the block on the bed joints was principally along the edges of the block, and the interior portions of the bed joints were not completely filled. already in place and by heavily buttering the vertical edges of this block. The next block was then placed on the bed joint and shoved horizontally into position. Filling of the upper portion of the joint was completed by slushing in mortar from above. The average thickness of the head joints was 0.95 in.

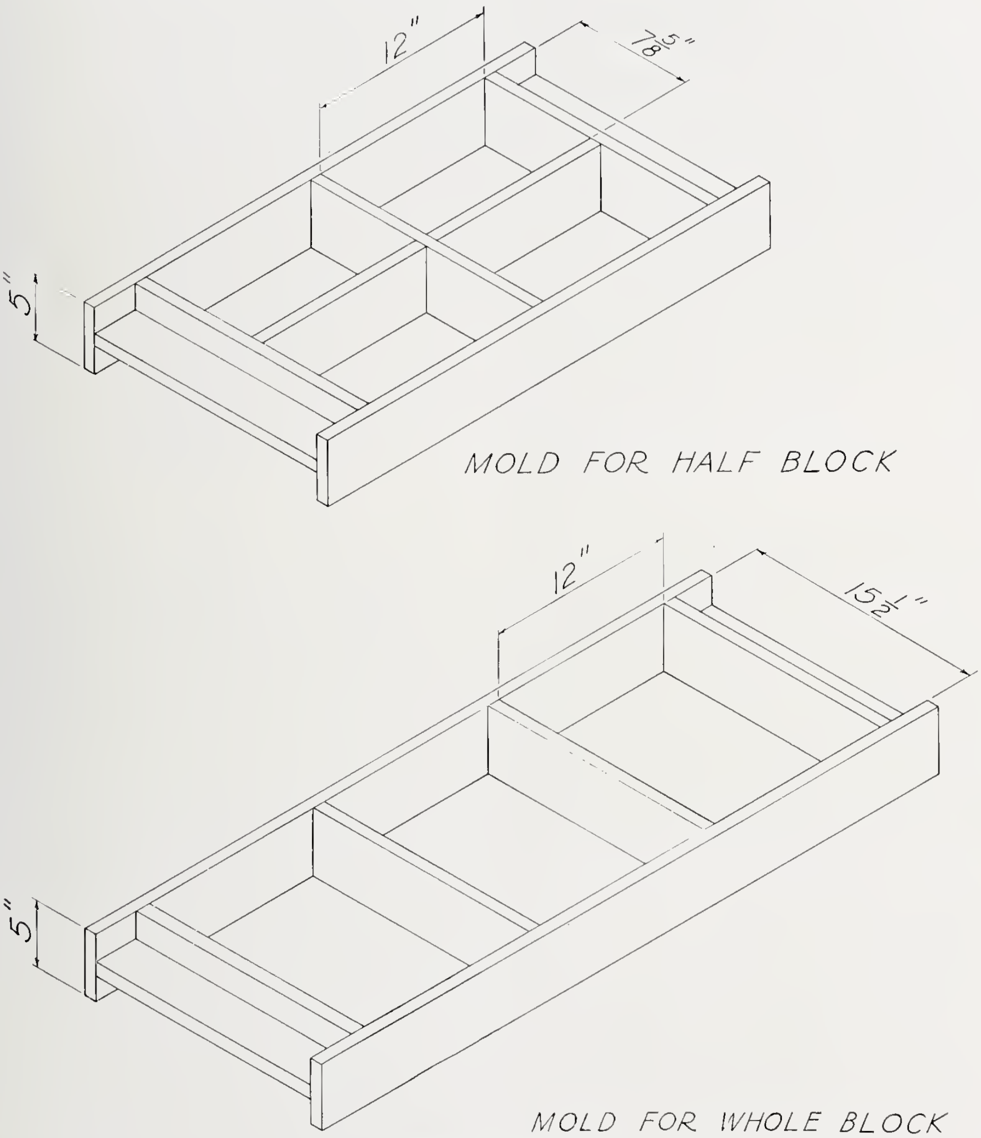

FIGURE 2.—*Block molds.*
Full and half size.

The average thickness of the bed joints was 0.51 in. at the face of the wall and 0.82 in. near the center.

The head joints were made by placing a thick coating of mortar against the face of a block

2. Bitudobe-Block Walls

(*a*) *General Information*

Bitudobe block are similar to adobe block, except that they contain an admixture of bituminous stabilizer and they must be made of earth that is free of alkaline salts. For bitudobe buildings it may be desirable and convenient to use a commercially prepared stabilizer.

FIGURE 3.—*Finishing adobe block.*

It is difficult properly to mix earth, water, and stabilizer in a pit. They should be mixed in a pug mill. Other types of mixers can be used only if the ingredients are accurately proportioned and if, after mixing, there remain no unbroken clods of earth.

Many houses in the Southwest are built of bitudobe block: and these units have been recognized in some of the building codes of that region. Unlike adobe, bitudobe walls are durable when exposed to driving rains.

(b) *Manufacture of Block*

The materials for the bitudobe block were mixed in a pug mill having a capacity of 3 ft ^{3}, illustrated in figure 7. The amount of bituminous stabilizer was 5.6 percent of the weight of the dry earth. This is equivalent to 0.328 gal per block, or 0.662 gal/ft ^{3} of dry earth.

The added water constituted 16 to 20 percent by weight of the dry earth. The bitudobe blocks were molded and dried in much the same manner as the adobe blocks. Just before being turned on edge to complete the drying, the top and bottom surfaces of the block as cast were scored. The scoring is shown in figure 8 and the method of laying in figure 9.

(c) *Control*

The essential controls for bitudobe block are the total moisture of the mixture and the amount of bituminous stabilizer. The moisture was controlled in the same way as for the adobe. To obtain the proper amount of stabilizer per block, the number of blocks per batch was determined by preliminary molding.

(d) *Construction of Wall*

The test walls were built in the same manner as the adobe specimens. The bed joints were furrowed and were built up higher near the wall faces than in the center. The block were laid cupped side down. Mortar for the bed joints was placed for one block at a time. The block were moved into alinement, after being placed on the mortar bed. Bearing on the beds was principally near the edges of the block and the bed joints at the center of the block were not always filled with mortar. The average thickness of the bed joints was 0.39 in. at the faces of the wall and 0.71 in. at the center.

Head joints varied considerably in thickness because of irregularities in block dimensions. Face joints were struck.

Since the block were water repellent and absorbed little water from the mortar, they were more difficult to lay than were adobe block and the mortar joints set slowly. Less water was needed in the mortar batches for bitudobe walls than in the mortar for adobe.

3. Monolithic Terracrete Walls

(a) *General Information*

Terracrete, consisting of damp earth having an admixture of portland cement as a stabilizer,

FIGURE 4.—*Removal of adobe molds.*
Half-sized block.

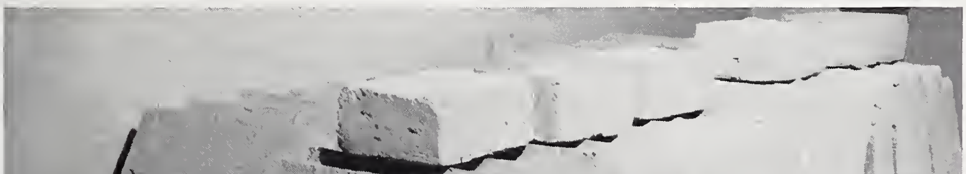

FIGURE 5.—*Stacked adobe blocks.*

was used in the construction of both monolithic and block specimens.

Utilization of terracrete for wall construction is a recent development, but considerable research has been devoted to portland-cement-stabilized earth for light-traffic highways by the Portland Cement Association.

Figure 6.—*Construction of adobe-block wall.*

Resistance to weathering of terracrete mixtures may be determined by subjecting specimens to cycles of freezing and thawing and wetting and drying.

The optimum moisture for the maximum compacted density of the materials used in these walls also was determined by the Portland Cement Association. If the moisture content is less than 10 percent, the terracrete cannot be properly compacted and the wall surface will be granular and friable. If the moisture content is greater than 12 percent, the terracrete will adhere to the tamps and "flow" under blows. Therefore the allowable limits of moisture are 10 percent and 12 percent by dry weight of the mixture; the optimum is 11.2 percent.

(b) *Construction of Wall*

The materials for the specimens were mixed in a pug mill, shown in figure 10, and when the water was uniformly distributed the terracrete was ready for compacting in the forms.

The wall forms are shown in figure 11; they

Figure 7.—*Production of bitudobe mixture.*

consisted of a starting form, which rested on the steel-channel supports of the wall, and a continuation form, which was used after the starting form was removed. In general, the forms consisted of side panels, *B* (fig. 11); end gates, *C*; tie bolts, *D* and *E*; and alinement blocks, *F*.

The tamps used to compact the terracrete in the forms consisted of a steel plate 3½ in. square and ½ in. thick, welded to the end of a 2-in. pipe 8 in. long. A 1-in. pipe 4 ft 0 in. long was connected to the 2-in. pipe by a reducer. Dry sand was poured into the tamp until the weight was 15 lb. It is advisable to develop the procedure of erecting monolithic earth walls before attempting the construction of a building.

After the starting form was assembled, a 3½- to 4-in. layer of loose terracrete was distributed on the supporting channel and compacted by blows from the tamps dropping 4 to 6 in. The ramming of the first course is shown in figure 12. The top layer was then scored to a depth of ½ in. in a checkered design. Successive layers of terracrete were placed in the form in this manner until the wall was completed to within 4 in. of the top of the form. Each layer was about 2 in. thick. The starting form was then dismantled and the continuation form was assembled in position. Construction of the wall was resumed, and each layer of terracrete was tamped and scored as before. After completion, the walls were sprayed with water once a day for 3 days, and the holes in the wall left by the tie bolts were pointed with cement mortar.

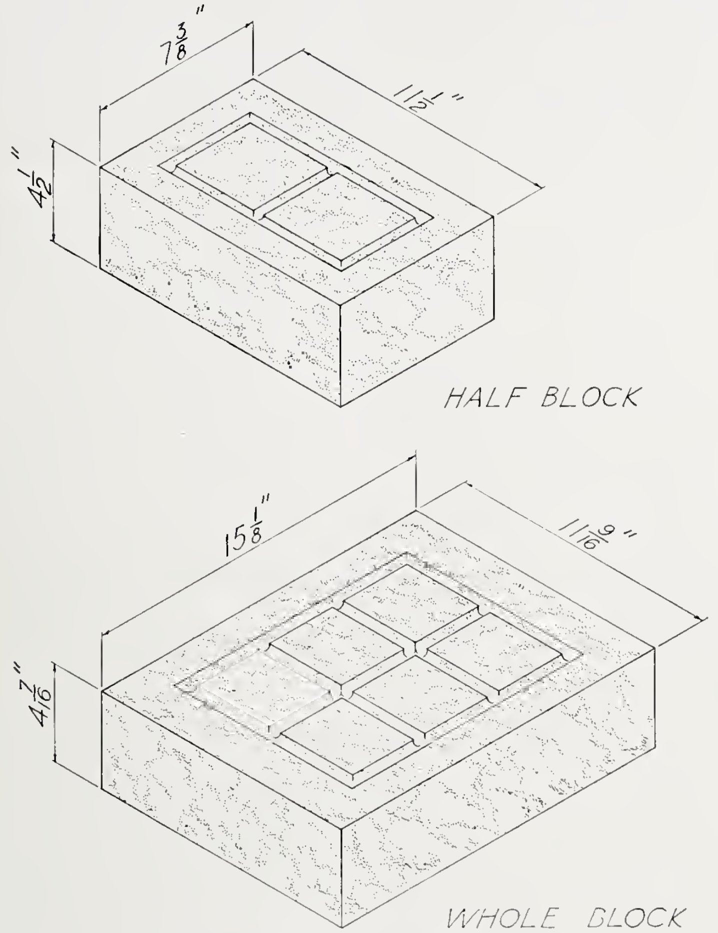

FIGURE 8.—*Bitudobe block.*
Full and half size, showing scoring.

Figure 9.—*Construction of bitudobe-block wall.*

(c) *Control*

The essential controls for monolithic terracrete are total moisture of the terracrete mixture, the quantity of portland cement, and the density of the compacted specimens. Samples of the mixture were taken periodically, dried over a gas flame, the moisture content computed, and the correct amount of water added to the subsequent batches.

4. Terracrete-Block Walls

(a) *General Information*

One distinct advantage of block over monolithic construction is that any defective unit may be discarded. When the large forms are removed from a section of monolithic wall, defective portions can be taken out and replaced only with difficulty.

The hydraulic press is an effective means of compacting terracrete block and makes commercial production possible.

(b) *Manufacture of Block*

Terracrete blocks for the test specimens were made from a mixture like that used in the mono-

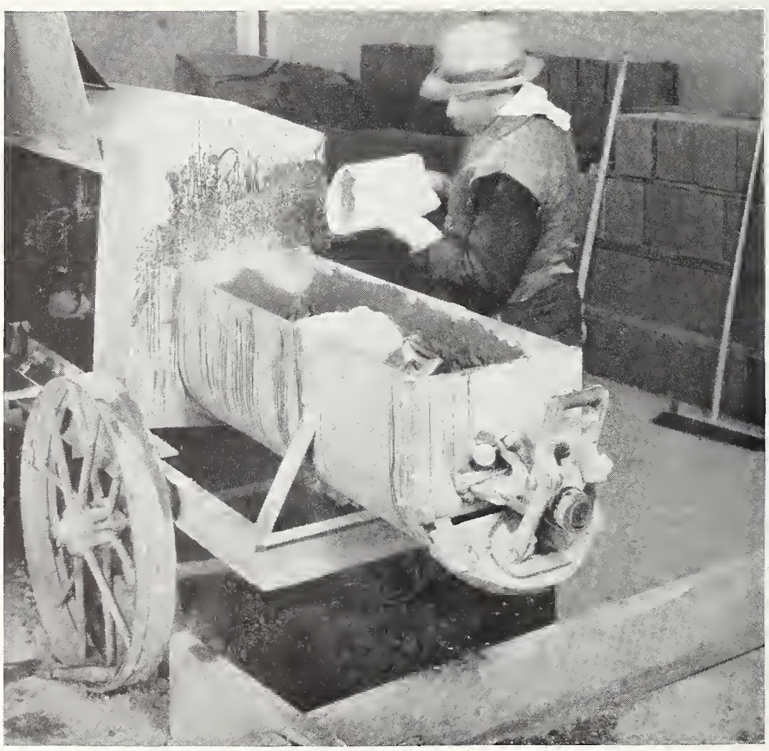

Figure 10.—*Production of terracrete mixture.*

lithic terracrete specimens. The blocks were compacted in a hydraulic press, shown in figure 13, which consisted of a pump driven by a 3-hp gasoline engine, a piston-and-cylinder assembly, and a mold. Oil in the cylinder was compressed to a maximum pressure of 1,200 lb/in.². One top was then securely closed, and a load was applied to the loose mixture until the maximum oil pressure was reached and immediately released. Half blocks were made by inserting a $\frac{3}{8}$-in. steel separator in the mold dividing the $10\frac{3}{8}$-in. dimension into equal parts.

FIGURE 11.—*Equipment for construction of walls DD and DF.*
A, tamp; *B*, side panel; *C*, end gate; *D* and *E*, tie bolts; *F*, alinement blocks.

face of the mold was mounted on the piston rod; the opposite face was attached to the frame of the press. The side, top, and bottom faces of the mold were not attached to the end faces but were free to move in the direction of motion of the piston, so that both ends of the block could be compacted to nearly the same density.

With only the top open, the mold was filled level full with loose terracrete mixture. The blocks were stacked four high and covered with wet burlap for 3 days.

K. W. Shell, of the Portland Cement Association, assisted in the molding of the terracrete blocks.

(c) *Control*

The methods of control were the same for the terracrete blocks as for the monolithic terracrete except that the blocks were used to determine the density of the compacted terracrete mixture.

(d) *Construction of Wall*

In erecting the specimen walls the bed joints were furrowed and were built up higher near the wall faces than in the center and only sufficient mortar for one block at a time was placed in the bed joints. The blocks were lifted into the wall by hand or with a brick tong and were moved into alinement by heavy blows from a mason's hammer. The head joints were made by plastering mortar against the face of a block already in place and by heavily buttering the vertical edges of this block. After hammering the block into alinement, the filling of the head joints was completed by slushing in mortar from above. It was difficult to completely fill the 8- by 12-in. head joints by slushing; and after demolition of the walls, portions of the interior faces of some of the blocks were devoid of adhering mortar, indicating that some of the head joints had not been completely filled.

FIGURE 12.—*Construction of walls DD and DE.*
First course. G, vertical tie bolts.

The average joint thickness was 0.64 in. for the bed joints and 0.48 in. for the head joints

5. RAMMED-EARTH WALLS

(a) *General Information*

The mixture for rammed earth ("earth" and water) was pulverized by turning the moistened earth with shovels. The moisture was 11.2 percent by dry weight of the earth.

There has been some construction of rammed-earth houses throughout the country; several buildings, including a large church near Sumter, S. C., built between 1820 and 1854, are still in good condition. A rammed-earth house near Washington, D. C., was erected 160 years ago; and other structures have been built more recently.

a rammed-earth wall should not be friable and should have adequate resistance to weathering. In general, satisfactory earth will have a high percentage of sand, preferably uniformly graded from fine to coarse, and a low percentage of clay.

Earth and water were mixed to a brushing consistency (dagga plaster) and applied to the faces of the structural- and water-permeability-test specimens.

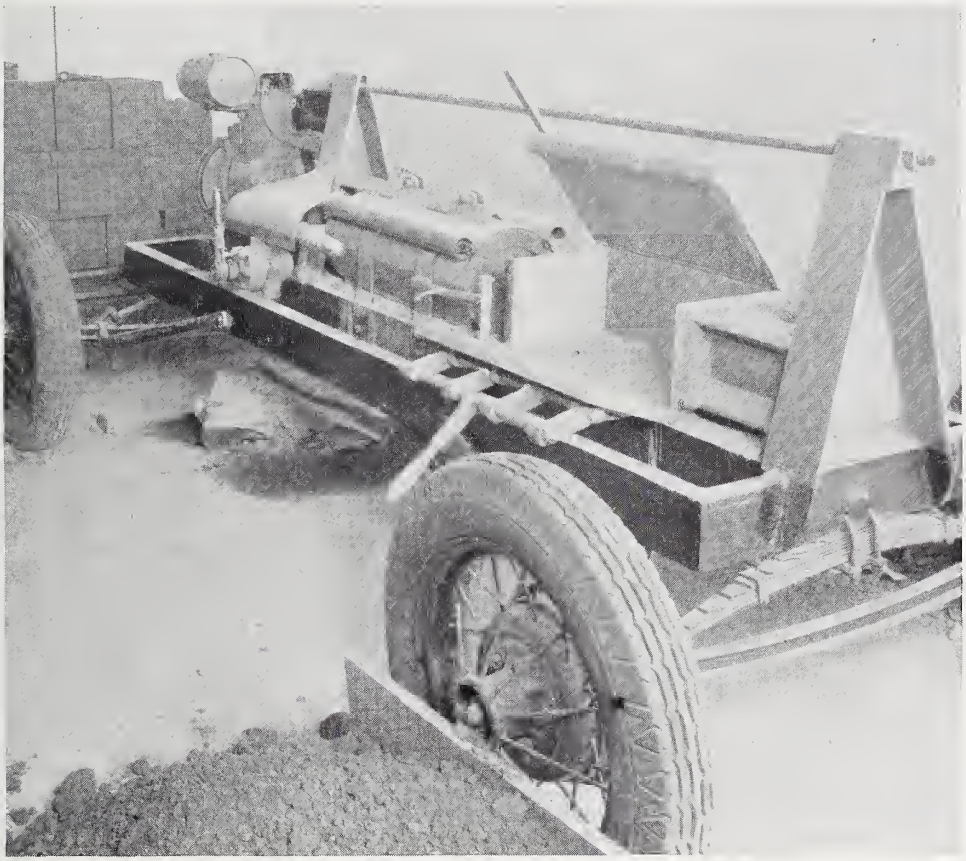

FIGURE 13.—*Hydraulic press for terracrete blocks.*

(*b*) *Construction of Wall*

The method of constructing the rammed-earth specimens was like that used for the monolithic terracrete walls.

Earth to be suitable for rammed-earth walls should pulverize without unbroken clods. When rammed, the initial strength should be sufficient to prevent damage during construction; the final strength should be adequate for the particular building. There should be a minimum shrinkage of the earth while curing to prevent cracks in the wall. The surface of

(*c*) *Control*

The essential control in building rammed-earth walls is the total moisture content of the mixture.

The optimum moisture content was 11.2 percent by dry weight. The allowable limits were 10 percent and 12 percent. Samples were taken periodically, dried over a gas flame, the moisture content computed, and the correct amount of water added to the subsequent batches. If the moisture were less than 10 percent, the mixture could not be properly compacted, also the wall surface would be granular and friable. If the moisture content were greater than 12 percent, the mixture adhered to the tamps and "flowed" under the blows.

IV. STRUCTURAL PROPERTIES

Except as indicated, the specimens were tested in accordance with report BMS2, which report also gives the requirements for the specimens and describes the presentation of the results of the tests, particularly the load-deformation graphs.

For the structural-property tests the constructions were assigned symbols in accordance with table 7, and 60 specimens were assigned the designations given in table 8.

TABLE 7.—*Construction symbols for structural tests*

Type of wall	Structural symbol	Admixture	Remarks
Adobe block	*DB*	None	Hand molded.
Bitudobe block	*DC*	Emulsified asphalt	Do.
Terracrete, monolithic.	*DD*	Portland cement	Hand rammed.
Terracrete block	*DE*	do	Machine pressed.
Rammed earth, monolithic.	*DF*	None	Hand rammed.

TABLE 8.—*Specimen designations for structural tests, walls DB, DC, DD, DE, and DF*

Specimen designation	Load	Load applied
C1, C2, C3	Compressive	Upper end.
T1, T2, T3	Transverse	Either face.
P1, P2, P3	Concentrated	Do.
I1, I2, I3	Impact [a]	Do.
R1, R2, R3	Racking	Near upper end.

[a] The impact and concentrated loads were applied to the same specimens, the impact load first.

For the transverse and impact loads, only three specimens were built for each load, because the specimens were symmetrical about a vertical plane midway between the faces; hence the results for transverse and impact loads applied to one face should be identical with those obtained by applying loads to the opposite face. The concentrated loads were applied to one face only for the same reason.

Under the compressive load the shortening was measured over the entire length of the specimen by compressometers attached to the steel plates through which the load was applied; not to the specimen itself, as described in BMS2.

The lateral deflections under compressive loads were measured with a deflectometer of fixed gage length, which consisted of a light (duralumin) tubular frame having a leg at one end and a hinged plate at the other. The deflectometer in a vertical position was attached near the upper end of the specimen by clamping the hinged plate to either face. The gage length (distance between the points of support) was 7 ft. 6 in. A dial micrometer was mounted on the frame at midlength, with the spindle in contact with the face of the specimen.

The dial was graduated to 0.001 in. and readings were recorded to the nearest division. There were two deflectometers, one near each edge of the specimen. This method of measurement was used instead of the taut-wire mirror-scale method described in BMS2.

For the transverse and impact loads the specimens were vertical. The lateral deflections under transverse load were measured in the same way as for the compressive load.

The indentation under concentrated load and the set after the load was removed were measured, instead of the set only as described in BMS2. The apparatus is shown in figure 14.

The load was measured by means of a ring dynamometer and was applied through the beam, *A*, to which a steel disk, *B*, was rigidly attached. Two dials, one of which is shown at *C*, were supported by a crossbar, *D*, also fastened to the beam. Each spindle was 8 in. from the center of the disk. The micrometers were graduated to 0.001 in., and readings were recorded to the nearest division. The initial reading (average of the micrometer readings) was observed under no load. A load was applied to the disk, and the average of the micrometer readings minus the initial reading was taken as the depth of the indentation under load. The set after the load was removed was determined similarly.

The deformations under racking loads were measured with a right-angle deformeter, consisting of a steel channel and a steel angle braced to form a rigid connection. In use the channel of the deformeter rested along the top of the specimen, with the steel angle extending downward in the plane of the specimen. Two pins passed snugly through holes in the channel into the top of the specimen. A dial micrometer was attached to the steel angle. The spindle of the micrometer was in contact with the edges of the specimen. The gage length (distance from the top of the specimen to the spindle of the micrometer) was 6 ft 8 in. The micrometer was graduated in 0.001 in., and readings were recorded to the nearest tenth of a division. This deformeter was used instead of the taut-wire mirror-scale method described in BMS2.

For the compressive tests the speed of the movable head of the testing machine was adjusted to 0.044 in./min.

The tests were begun February 19, 1940, and completed June 21, 1940.

1. Adobe-Block Wall *DB*

(*a*) *Description*

Wall construction *DB* was plain adobe block laid in cement-lime mortar. The block and mortar were exposed on both faces.

The full-sized blocks were $11\frac{11}{16}$ by $15\frac{1}{4}$ by $4\frac{15}{16}$ in. and weighed 53 lb as laid. The half-sized blocks were $11\frac{9}{16}$ by $7\frac{7}{16}$ by $4\frac{15}{16}$ in. and weighed 25 lb as laid. They are shown in figure 15. The moisture content of the blocks, as laid, was 1.5 percent by dry weight. The modulus of rupture, flatwise, on a span of 14 in. was 42 lb/in². The compressive strength, flatwise, of the full-sized blocks was 500 lb/in.² and of the half-sized blocks 265 lb/in². The compressive strength of these blocks was greater the greater the loaded area.

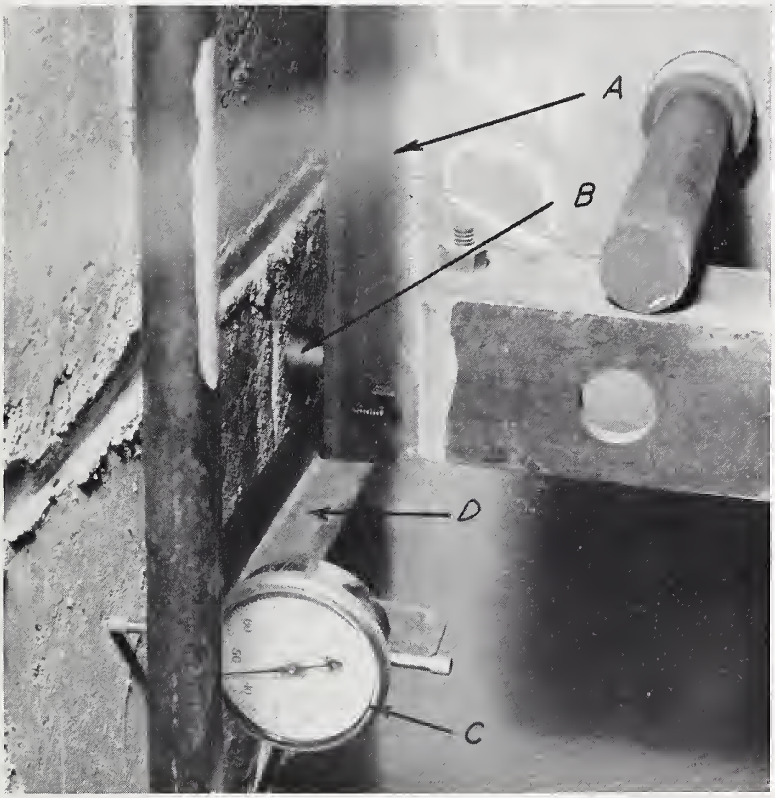

FIGURE 14.—*Apparatus for concentrated-load test.*
A, load beam; *B*, steel disk; *C*, dial micrometer; *D*, crossbar.

An attempt was made to determine the moisture absorption of the block in accordance with ASTM C67–37, Standard Methods of Testing Brick.[1] This was not accomplished, because the loss of weight from erosion was greater than the gain in weight from moisture absorption.

Two cylinders, 4 in. in diameter and 4 in.

[1] Am. Soc. Testing Materials Supplement to Book of ASTM Standards, p. 78–82 (1937).

high, were made of adobe for each specimen. The compressive strengths of the cylinders are given in table 9.

Four-foot adobe-block wall specimens.—The 4-ft wall specimens were 20 courses high, except *DB–T2* and *T3*, which were 21 courses. The specimens shown in figure 16 (20 courses high) were 8 ft 2½ in. high, 4 ft 0³⁄₁₆ in. wide, and 11¹³⁄₁₆ in. thick. The texture of the adobe walls is shown in figure 17.

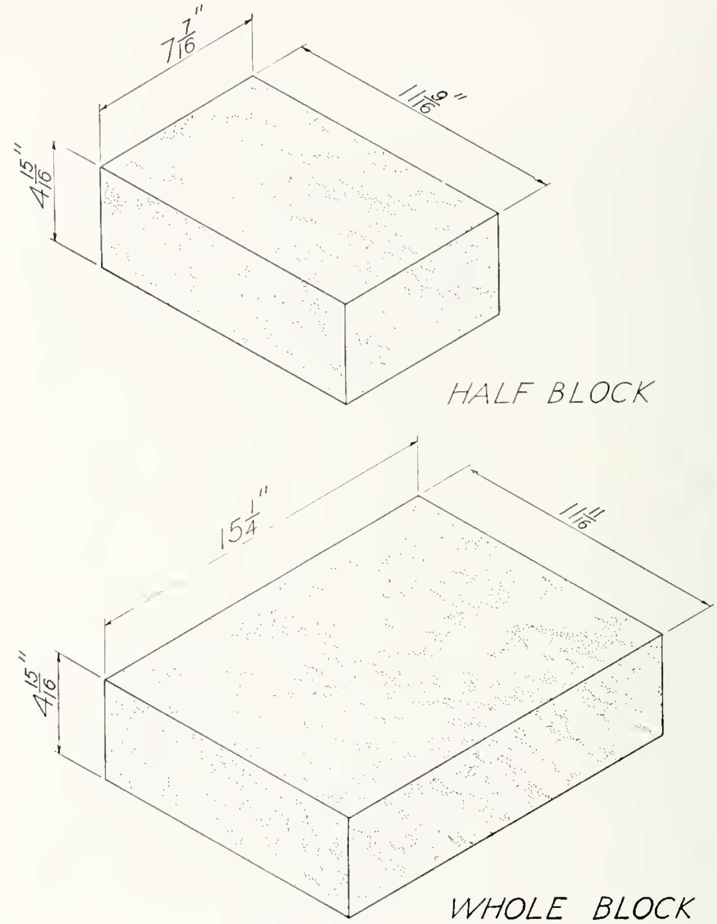

FIGURE 15.—*Adobe block.*
Full and half size.

TABLE 9.—*Compressive strength of adobe cylinders for wall DB*

[The compressive strength of the cylinders was determined by the Masonry Construction Section of the National Bureau of Standards on the day the corresponding wall specimens were tested]

Specimen	Compressive strength [a]	Specimen	Compressive strength [a]
	lb/in.²		*lb/in.²*
C1	198	*I2 (P2)* [b]	203
C2	230	*I3 (P3)* [b]	208
C3	200	*R1*	183
T1	198	*R2*	185
T2	188	*R3*	175
T3	213		
I1 (P1) [b]	223	Average	200

[a] Each value represents the average of 2 cylinders.
[b] The impact and concentrated loads were applied to the same specimens, the impact load first.

Eight-foot adobe-block wall specimens.—The 8-ft wall specimens shown in figure 18 were similar to the 4-ft specimens. The specimens were 8 ft 5¼ in. high, 7 ft 11⁷⁄₁₆ in. wide, and 11¾ in. thick. There were 21 courses in each specimen.

(*b*) *Compressive Load*

Specimen *DB–C2* under compressive load is shown in figure 19. The results of the compressive tests on specimens *DB–C1, C2, and C3* are shown in table 10 and figures 20 and 21.

The shortenings and sets in figure 20 are computed for a height of 8 ft. The gage length of the compressometers was 8 ft 2½ in.

Under the maximum load vertical cracks appeared in the edges of specimens *C1* and *C3* near the inside face (the face nearer the load line) above midheight. Cracks appeared similarly in specimen *C2* under a load of 12.0 kips/ft. At 13.7 kips/ft the inside face cracked vertically near one edge. Under the maximum load many additional cracks were observed.

(*c*) *Transverse Load*

The results of the transverse tests are given in table 10 and figure 22 for specimens *DB–T1*, *T2*, and *T3*.

In specimen *T1* at a load of 37.6 lb/ft² there was failure of the bond in a bed joint between the loading rollers, and in specimens *T2* and *T3* at 48.6 lb/ft². Greater loads increased the width of the bond cracks in the face not loaded. Under the maximum load on *T3* the blocks spalled on the loaded face between the loading rollers.

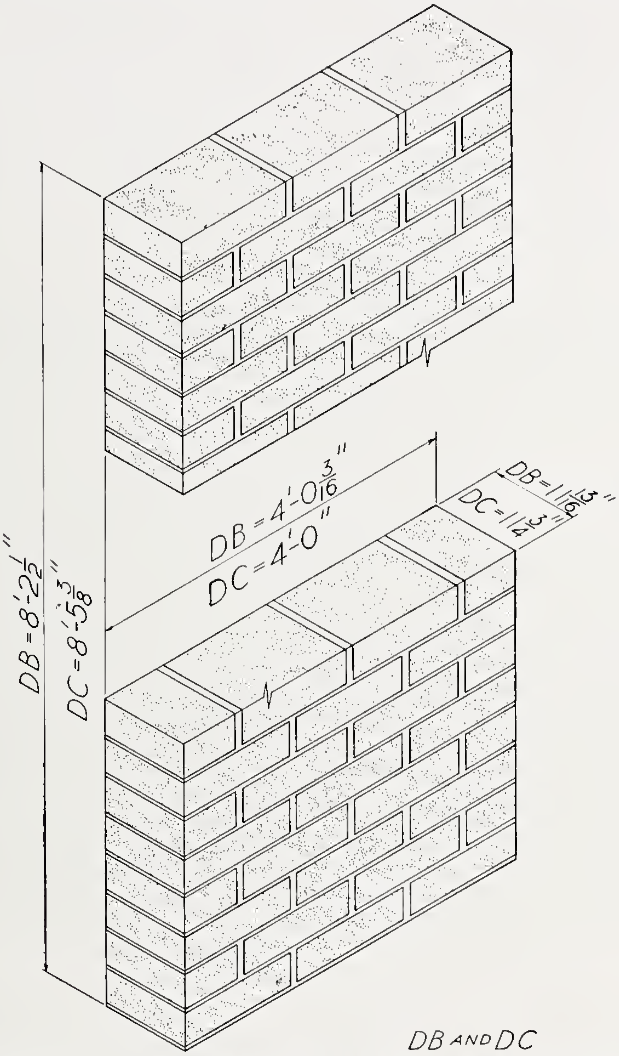

FIGURE 16.—*Four-foot wall specimen, adobe and bitudobe block.*

(*d*) *Concentrated Load*

The results of the concentrated tests are given in table 10 and in figure 23.

The concentrated loads were applied to the center of an adobe block. The set after a load of 1,000 lb had been applied was 0.049 in. in specimen *P1*, 0.076 in. in *P2*, and 0.109 in. in *P3*. No other effect was observed.

(*e*) *Impact Load*

The results of the impact tests of specimens *DB–I1*, *I2*, and *I3* are shown in table 10 and figure 24.

The impact loads were applied to the center of the specimen, the sandbag striking the adobe blocks. There was failure of the bond in a bed joint at midheight at a drop of 2.5 ft in specimens *I1* and *I2* and of 1.5 ft in *I3*. At a drop of 10 ft on specimen *I1* there also was a bond crack in a bed joint one course above the initial bond crack.

(*f*) *Racking Load*

The results of the racking tests on wall specimens *DB–R1*, *R2*, and *R3* are shown in table 10 and in figure 25.

Under the maximum load each specimen cracked diagonally from the loading plate to the stop through the blocks and mortar joints.

The price of this construction in Washington, D. C., as of July 1937, was \$0.26/ft².

2. Bitudobe-Block Wall *DC*

(*a*) *Description*

Wall *DC* was bitudobe block laid in cement-lime mortar. The blocks were earth with an admixture of bituminous stabilizer. The block and mortar were exposed on both faces.

The full-sized bitudobe blocks were 11 9/16 by 15 1/8 by 4 7/16 in. and weighed 51 lb. as laid. The half-sized blocks were 11 1/2 by 7 3/8 by 4 1/2 in. and weighed 26 lb. as laid. They are shown in figures 8 and 9.

Figure 17.—*Texture of wall DB, adobe block.*

The moisture content of the blocks as laid was 2.3 percent by dry weight. The modulus of rupture, flatwise, on a span of 14 in., was 42 lb./in.² The compressive strength of the full-sized block, flatwise, was 630 lb./in.² and of the half-sized block 365 lb./in². The compressive strength of these blocks was greater the greater the loaded area.

The moisture absorption, determined in accordance with ASTM C67–37, was 0.8 percent by weight.

Two cylinders of bitudobe, 4 in. in diameter and 4 in. high, were made for each specimen. The compressive strengths of the bitudobe cylinders are given in table 11.

Four-foot bitudobe wall specimens.—The 4-ft wall specimens shown in figure 16 were 8 ft 5⅜ in. high, 4 ft 0 in. wide, and 11¾ in. thick. Each specimen was 21 courses high. The texture of the wall is shown in figure 26.

(b) *Compressive Load*

The results of the compressive tests for wall specimens *DC–C1*, *C2*, and *C3* are shown in table 10 and in figures 27 and 28.

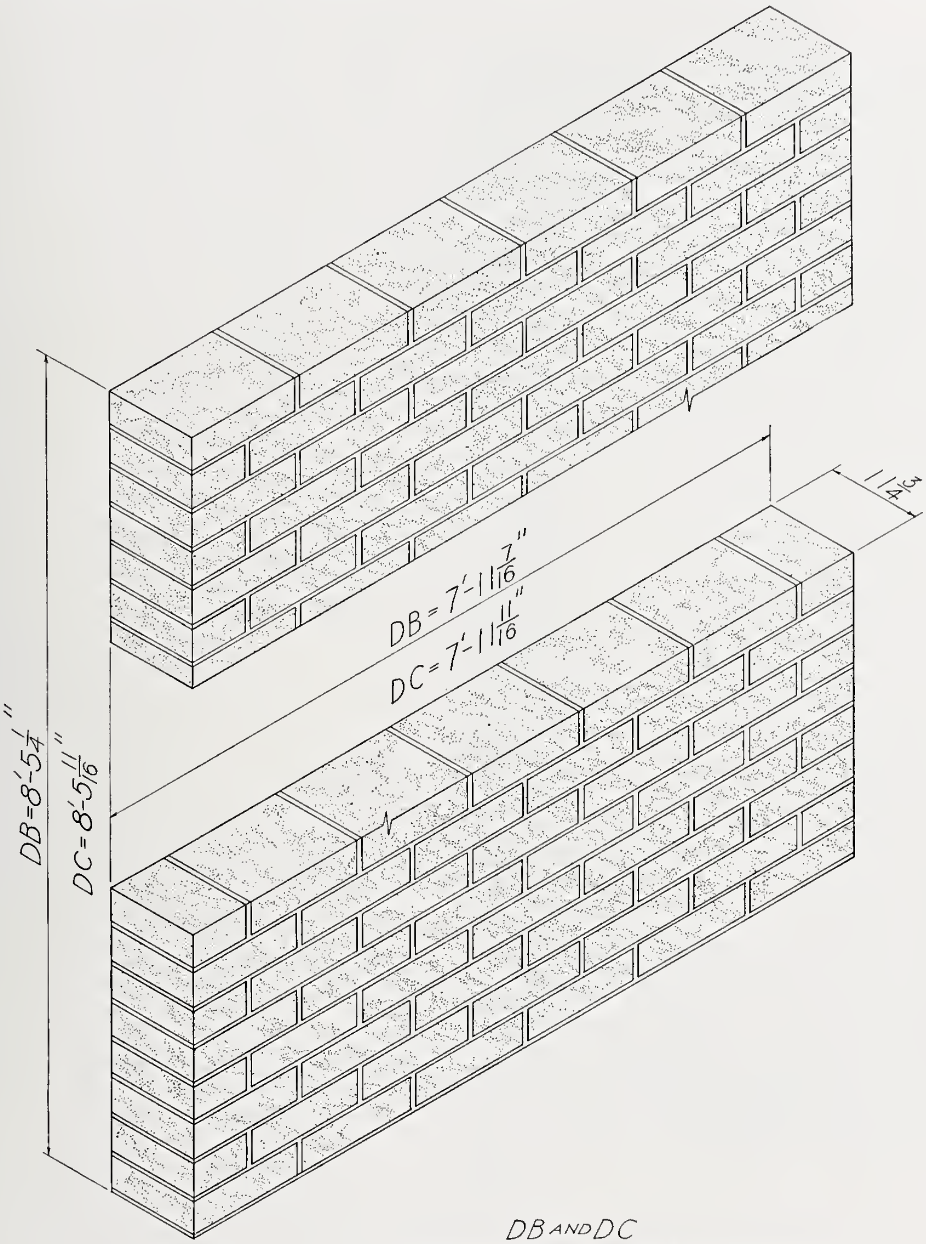

FIGURE 18.—*Eight-foot wall specimen, adobe and bitudobe block.*

Eight-foot bitudobe wall specimens.—The 8-ft wall specimens shown in figure 18 were 8 ft 5 11/16 in. high, 7 ft 11 11/16 in. wide, and 11¾ in. thick. Each specimen was 21 courses high and was similar to the 4-ft specimens.

The shortenings and sets given in figure 27 are computed for a height of 8 ft. The gage length of the compressometers was 8 ft 5 11/16 in.

Unless stated otherwise, the compressive load was applied to the inside face (the face nearer the load line).

Under a load of 11.00 kips/ft on specimen *DC–C1* there was a vertical crack in the course second from the top. At 11.72 kips/ft a vertical crack near one edge extended through the head joints and blocks from midheight to the top of the wall. In specimen *C2* there was a vertical crack through several courses near midheight under a load of 10.00 kips/ft. At 10.25 kips/ft there was a vertical crack in

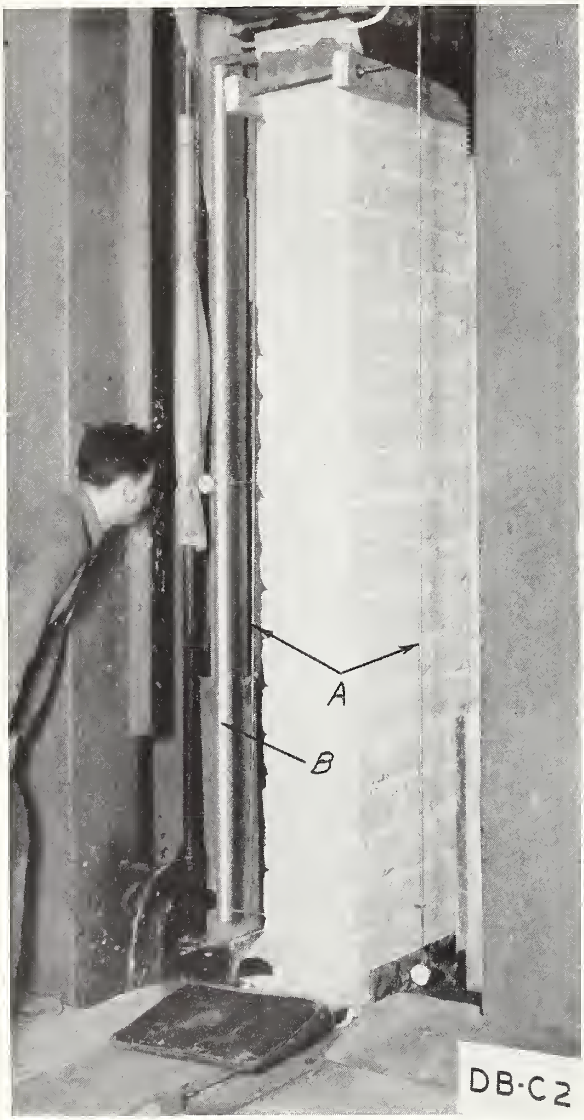

FIGURE 19.—*Wall specimen DB–C2 under compressive load.*

A, compressometer; *B*, deflectometer.

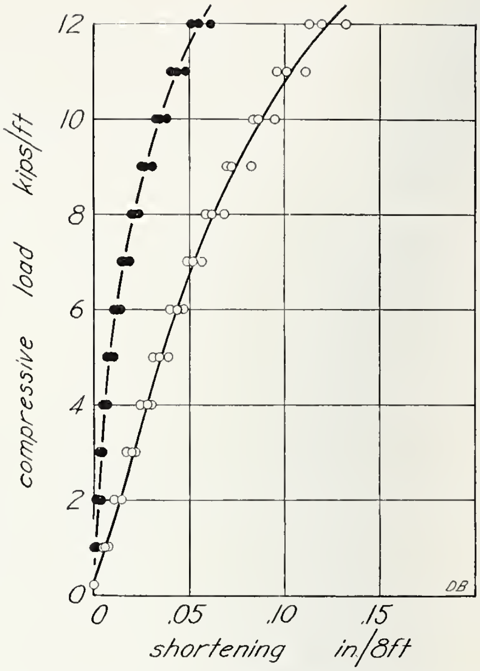

FIGURE 20.—*Compressive load on wall DB.*

Load-shortening (open circles) and load-set (solid circles) results for specimens *DB–C1, C2,* and *C3*. Load applied 3.94 in. (one-third the thickness) from one face. The loads are in kips per foot of actual width of specimen.

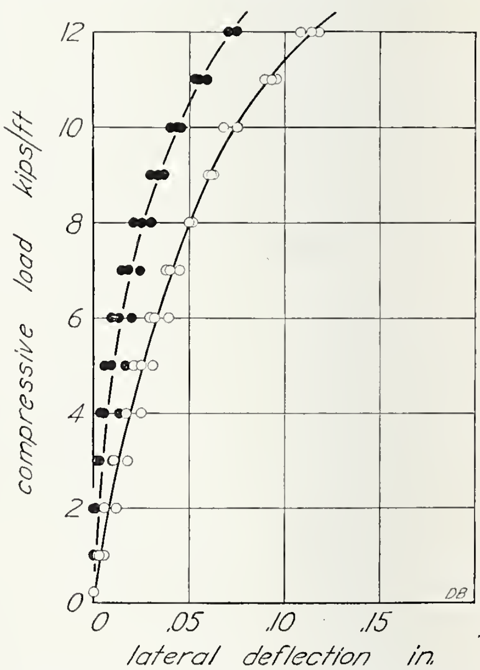

FIGURE 21.—*Compressive load on wall DB.*

Load-lateral deflection (open circles) and load-lateral set (solid circles) results for specimens *DB–C1, C2,* and *C3*. Load applied 3.94 in. (one-third the thickness) from one face. The loads are in kips per foot of actual width of specimen. The deflections and sets are for a gage length of 7 ft. 6 in., the gage length of the deflectometers.

TABLE 10.—*Structural properties of earth walls DB, DC, DD, DE, and DF*

Type of wall	Structural symbol	Weight		Load									
				Compressive [a]		Transverse; span 7 ft 6 in.		Concentrated [b]		Impact; [c] span 7 ft 6 in.		Racking	
				Specimen	Maximum load	Specimen	Maximum load	Specimen	Maximum load	Specimen	Maximum height of drop	Specimen	Maximum load
		lb/ft²	*lb/ft³*		[d] *Kips/ft*		*lb/ft²*		*lb*		*ft*		[d] *Kips/ft*
Adobe block	*DB*	121	124	*C1*	13.61	*T1*	60.0	*P1*	[e] 1,000	*I1*	[f] 10.0	*R1*	2.49
				C2	13.94	*T2*	56.9	*P2*	[e] 1,000	*I2*	[f] 10.0	*R2*	2.73
				C3	14.56	*T3*	60.0	*P3*	[e] 1,000	*I3*	[f] 10.0	*R3*	2.60
Average					14.03		59.0		[e] 1,000		[f] 10.0		2.61
Bitudobe block	*DC*	117	120	*C1*	11.87	*T1*	82.0	*P1*	[e] 1,000	*I1*	[f] 10.0	*R1*	3.20
				C2	10.87	*T2*	80.0	*P2*	616	*I2*	5.0	*R2*	2.80
				C3	11.13	*T3*	76.7	*P3*	[e] 1,000	*I3*	4.5	*R3*	2.81
Average					11.29		79.6						2.94
Terracrete, monolithic	*DD*	157	135	*C1*	97	*T1*	63.9	*P1*	[e] 1,000	*I1*	[f] 10.0	*R1*	[f] 6.25
				C2	110	*T2*	90.0	*P2*	[e] 1,000	*I2*	5.5	*R2*	[f] 6.25
				C3	110	*T3*	159.2	*P3*	[e] 1,000	*I3*	4.0	*R3*	[f] 6.25
Average					106		104.0		[e] 1,000				[f] 6.25
Terracrete block	*DE*	134	137	*C1*	119	*T1*	100	*P1*	[e] 1,000	*I1*	9.0	*R1*	
				C2	124	*T2*	102	*P2*	[e] 1,000	*I2*	7.5	*R2*	[f] 6.28
				C3	108	*T3*	135	*P3*	[e] 1,000	*I3*	4.5	*R3*	[f] 4.80
Average					117		112		[e] 1,000		7.0		
Rammed earth, monolithic	*DF*	152	130	*C1*	17.12	*T1*	54.1	*P1*	[e] 1,000	*I1*	7.0	*R1*	1.85
				C2	13.07	*T2*	67.0	*P2*	[e] 1,000	*I2*	7.5	*R2*	1.62
				C3	12.25	*T3*	57.1	*P3*	[e] 1,000	*I3*	8.0	*R3*	2.00
Average					14.15		59.4		[e] 1,000		7.5		1.82

[a] Compressive loads were applied ⅓ the thickness of the wall from 1 face.
[b] Diameter of load disk is 1 in.
[c] The sandbag weighs 60 lb.
[d] A kip is 1,000 lb.
[e] Test discontinued; specimen undamaged.
[f] Test discontinued; specimen damaged.

TABLE 11.—*Compressive strength of bitudobe cylinders for wall DC*

The compressive strength of the cylinders was determined by the Masonry Construction Section of the National Bureau of Standards on the day the corresponding wall specimens were tested]

Specimen	Compressive strength [a]	Specimen	Compressive strength [a]
	lb/in.²		*lb/in.²*
C1	248	*I2 (P2)* [b]	298
C2	305	*I3 (P3)* [b]	270
C3	293	*R1*	304
T1	328	*R2*	283
T2	315	*R3*	269
T3	313		
I1 (P1) [b]	255	Average	290

[a] Each value represents the average of 2 cylinders.
[b] The impact and concentrated loads were applied to the same specimens, the impact load first.

one edge of the specimen near the top through one block. Under a load of 10.75 kips/ft two courses just above midheight crushed at a corner of the specimen. Under a load of 10.00 kips/ft on specimen *C3*, vertical cracks were observed in head joints above midheight. At 10.91 kips/ft one corner began to crush near the top. Under the maximum load on each specimen, additional cracks appeared and there was more crushing.

(*c*) *Transverse Load*

Wall specimen *DC–T2* under transverse load is shown in figure 29. The results for specimens *DC–T1*, *T2*, and *T3* are shown in table 10 and figure 30.

In specimen *DC–T1* a bond crack appeared on the face not loaded near midheight at a load of 70 lb/ft², and at a load of 80 lb/ft² the specimen ruptured transversely along this crack. Under the maximum load this crack was 1 in. wide. In specimen *T2* at a load of 60 lb/ft² transverse cracks were observed in three bed joints at midheight on the face loaded. Under the maximum load specimen *T2* ruptured transversely between the loading rollers; specimen *T3* ruptured transversely under a loading roller.

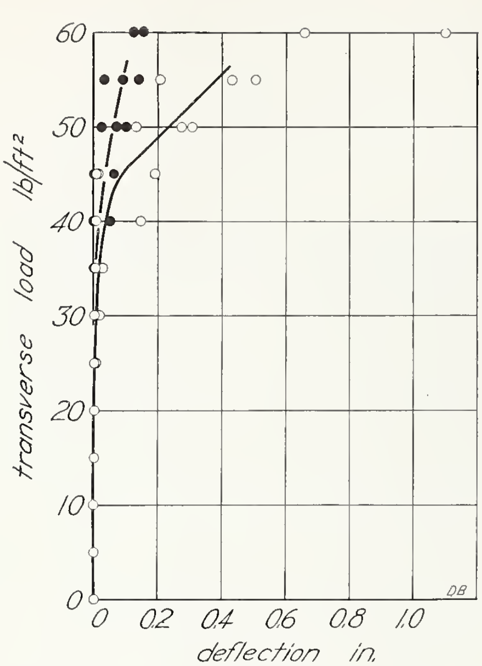

Figure 22.—*Transverse load on wall DB.*

Load-deflection (open circles) and load-set (solid circles) results for specimens *DB–T1, T2,* and *T3* on the span 7 ft. 6 in.

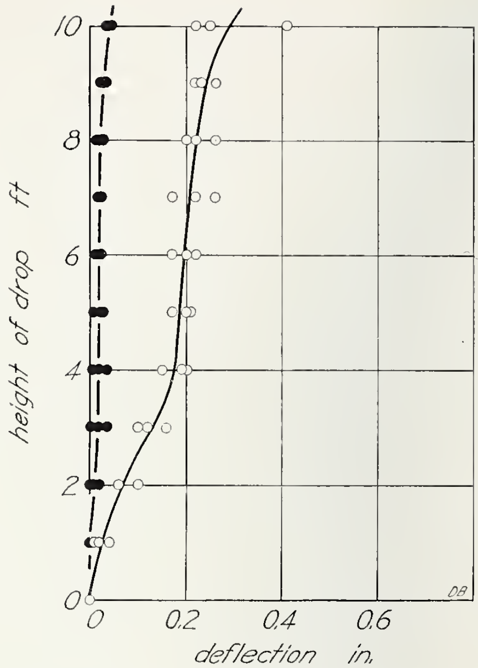

Figure 24.—*Impact load on wall DB.*

Height of drop-deflection (open circles) and height of drop-set (solid circles) results for specimens *DB–I1, I2,* and *I3* on the span 7 ft. 6 in.

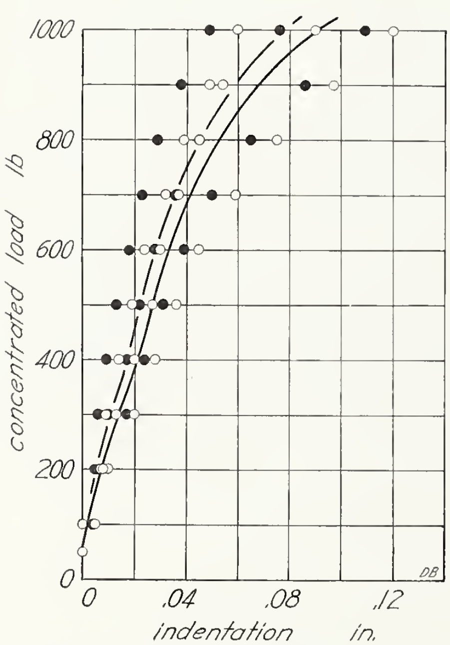

Figure 23.—*Concentrated load on wall DB.*

Load-indentation (open circles) and load-set (solid circles) results for specimens *DB–P1, P2,* and *P3.*

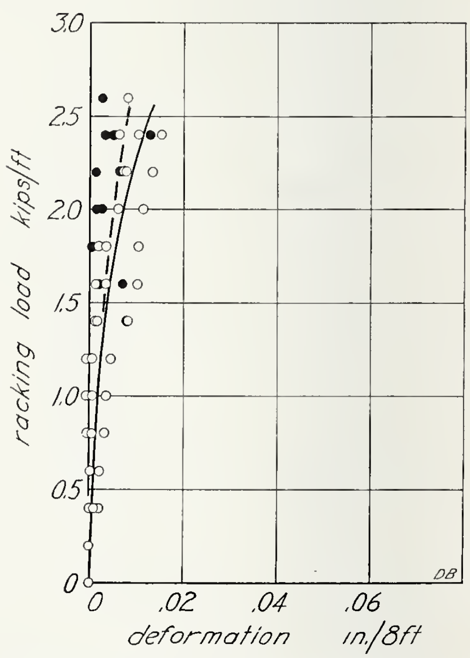

Figure 25.—*Racking load on wall OB.*

Load-deformation (open circles) and load-set (solid circles) results for specimens *DB–R1, R2,* and *R3.* The loads are in kips per foot of actual width of specimen.

FIGURE 26.—*Texture of wall DC, bitudobe brick.*

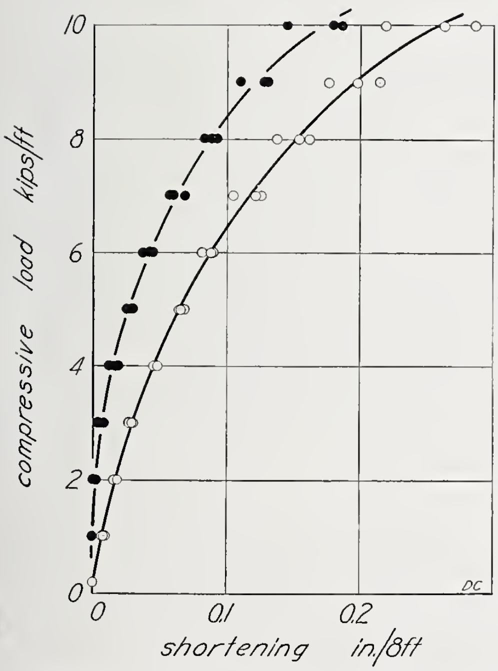

FIGURE 27.—*Compressive load on wall DC.*

Load-shortening (open circles) and load-set (solid circles) results for specimens *DC–C1, C2,* and *C3*. The load was applied 3.92 in. (one-third the thickness) from one face. The loads are in kips per foot of actual width of specimen.

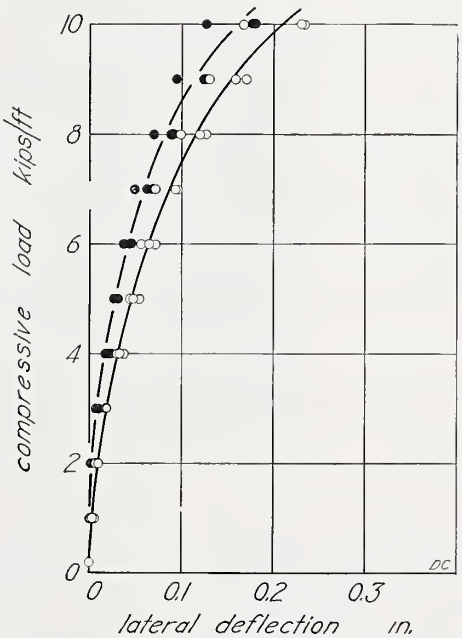

FIGURE 28.—*Compressive load on wall DC.*

Load-lateral deflection (open circles) and load-lateral set (solid circles) results for specimens *DC–C1, C2,* and *C3*. The load was applied 3.92 in. (one-third the thickness) from one face. The loads are in kips per foot of actual width of specimen. The deflections and sets are for a gage length of 7 ft. 6 in., the gage length of the deflectometer.

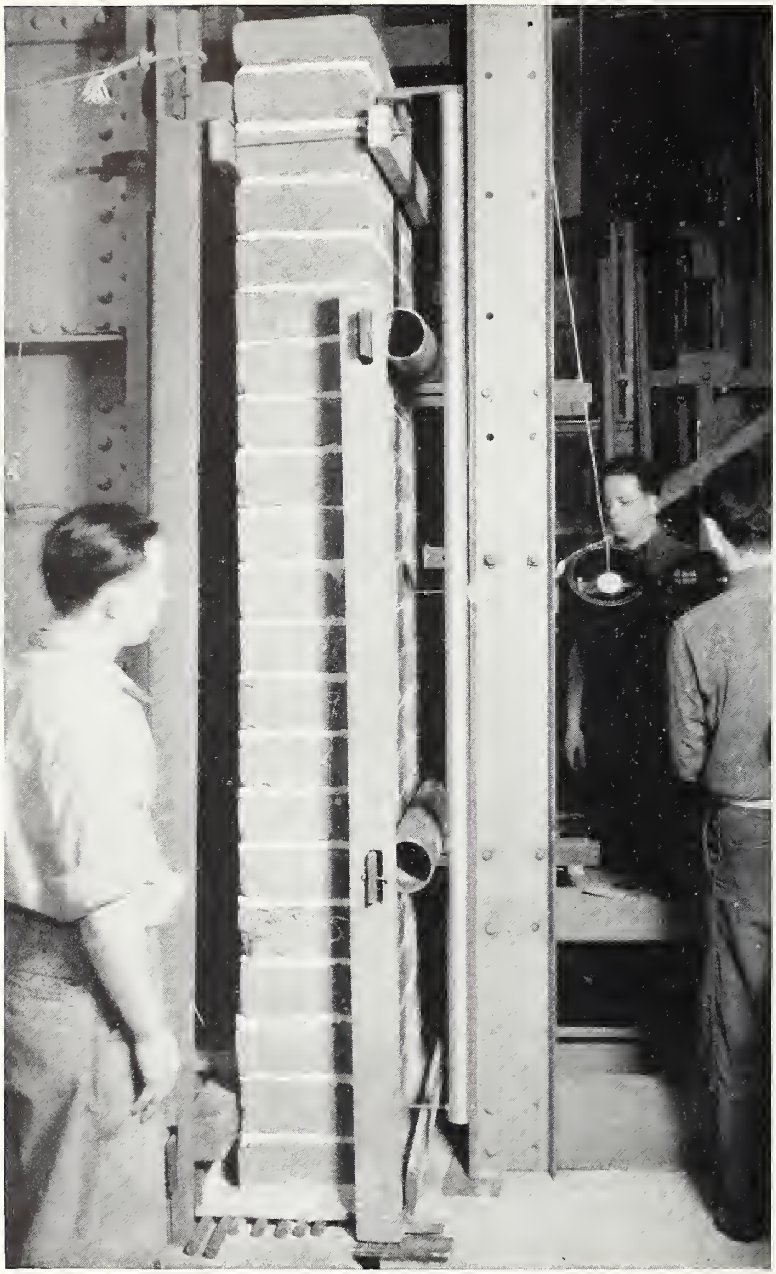

FIGURE 29.—*Wall specimen DC–T2 under transverse load.*

(*d*) *Concentrated Load*

The results of the concentrated tests on specimens *DC–P1*, *P2*, and *P3* are shown in table 10 and in figure 31.

After a load of 1,000 lb had been applied, the set in specimen *DC–P1* was 0.124 in. and in *P3* 0.056 in. Under the maximum load on specimen *P2* the loading disk punched into a cavity in the block.

(*e*) *Impact Load*

The results of the impact tests on specimens *DC–I1*, *I2*, and *I3* are given in table 10 and in figure 32.

In specimen *DC–I1* after a drop of 8.5 ft there was a failure of the bond in a bed joint at midheight on the face not struck; in specimen *I2*, after a drop of 4.0 ft; and in *I3*, after a drop of 2.0 ft. After the maximum

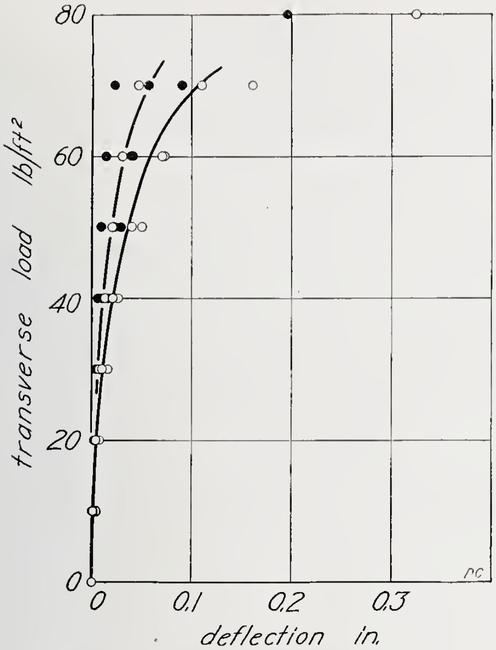

FIGURE 30.—*Transverse load on wall DC.*

Load-deflection (open circles) and load-set (solid circles) results for specimens *DC–T1, T2,* and *T3* on the span 7 ft. 6 in.

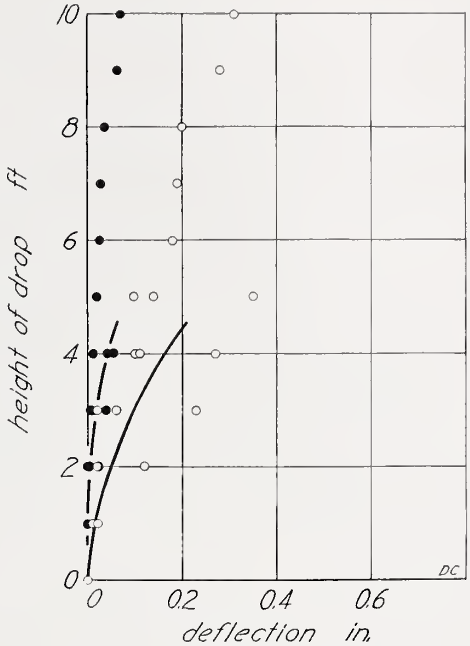

FIGURE 32.—*Impact load on wall DC.*

Height of drop-deflection (open circles) and height of drop-set (solid circles) results for specimens *DC–I1, I2,* and *I3* on the span 7 ft. 6 in.

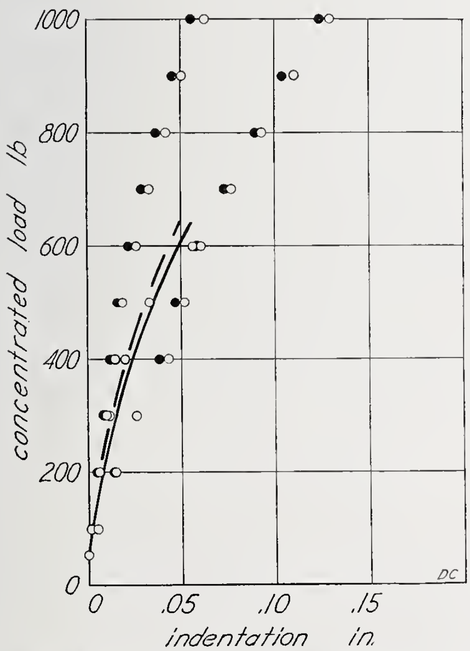

FIGURE 31.—*Concentrated load on wall DC.*

Load-indentation (open circles) and load-set (solid circles) results for specimens *DC–P1, P2,* and *P3.*

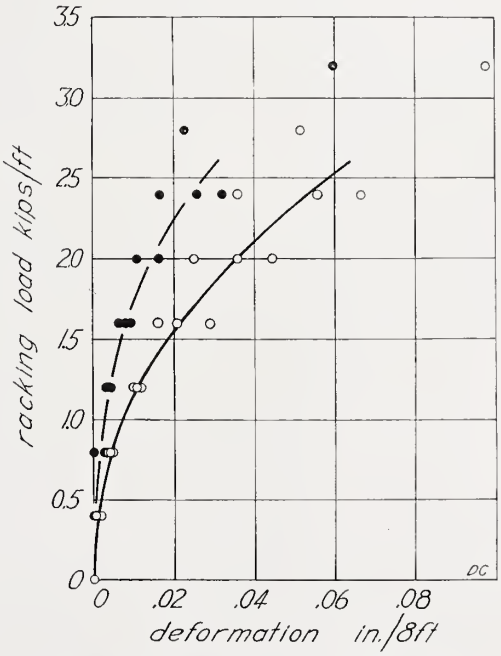

FIGURE 33.—*Racking load on wall DC.*

Load-deformation (open circles) and load-set (solid circles) results for specimens *DC–R1, R2,* and *R3.* The loads are in kips per foot of actual width of specimen.

height of drop on each specimen, the crack in the bed joints extended through the wall.

(*f*) *Racking Load*

The results of the racking tests on specimens *DC–R1*, *R2*, and *R3* are shown in table 10 and figure 33.

In specimen *DC–R1* at a load of 2.00 kips/ft there was a crack in a bed joint near the top of the wall and extending the full width. In specimens *R2* and *R3* at loads of 2.59 and 1.12 kips/ft, respectively, diagonal cracks appeared in the blocks near the center of the wall. Under the maximum load on each specimen there was a crack through the blocks and mortar joints diagonally from the loading plate to the stop.

The price of this construction in Washington, D. C., as of July 1937, was $0.33/ft².

3. Monolithic Terracrete Wall *DD*

(*a*) *Description*

Wall *DD* was a monolithic terracrete construction rammed by hand into wood forms. The terracrete was earth with an admixture of portland cement as a stabilizer. The terracrete was exposed on both faces.

One cylinder of terracrete, 8 in. in diam. and 8 in. high, was rammed for each specimen. The compressive strengths of the cylinders are given in table 12.

Table 12.—*Compressive strength of terracrete cylinders for wall DD*

[The compressive strength of the cylinders was determined by the Masonry Construction Section of the National Bureau of Standards on the day the corresponding wall specimens were tested]

Specimen	Compressive strength	Specimen	Compressive strength
	lb/in.²		*lb/in.²*
C1	1,220	*I2* (*P2*)[a]	680
C2	1,280	*I3* (*P3*)[a]	880
C3	1,140	*R1*	1,140
T1	820	*R2*	920
T2	880	*R3*	1,160
T3	940		
I1 (*P1*)[a]	990	Average	1,000

[a] The impact and concentrated loads were applied to the same specimens, the impact load first.

Four-foot monolithic terracrete wall specimens.—The 4-ft specimens shown in figure 34 were 8 ft 3 in. high, 4 ft 0³⁄₁₆ in. wide, and 1 ft 2 in. thick.

The texture of the walls is shown in figure 35.

Eight-foot monolithic terracrete wall specimens.—The 8-ft wall specimens shown in figure 36 were similar to the 4-ft specimens. They were 8 ft 3¹⁄₁₆ in. high, 8 ft 0⁹⁄₁₆ in. wide, and 1 ft 1⁷⁄₈ in. thick.

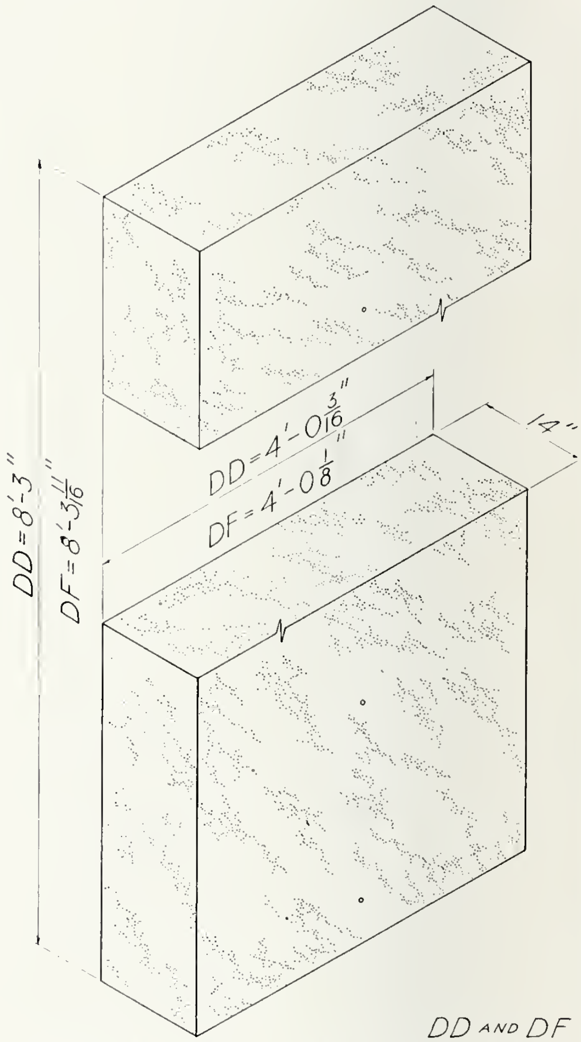

Figure 34.—*Four-foot monolithic wall specimen.*

(*b*) *Compressive Load*

The results for the compressive tests on *DD–C1*, *C2*, and *C3* are shown in table 10 and in figures 37 and 38.

The shortenings and sets given in figure 37 are computed for a height of 8 ft. The gage length of the compressometers was 8 ft 3⁷⁄₈ in.

In specimen *DD–C1* a transverse crack appeared on the inside face (the face nearer the load line) near the top and one edge of the specimen at a load of 88.0 kips/ft. Under a load of 97.4 kips/ft the inside face crushed and spalled along transverse lines near the top. In specimen *C2* at a load of 106 kips/ft there

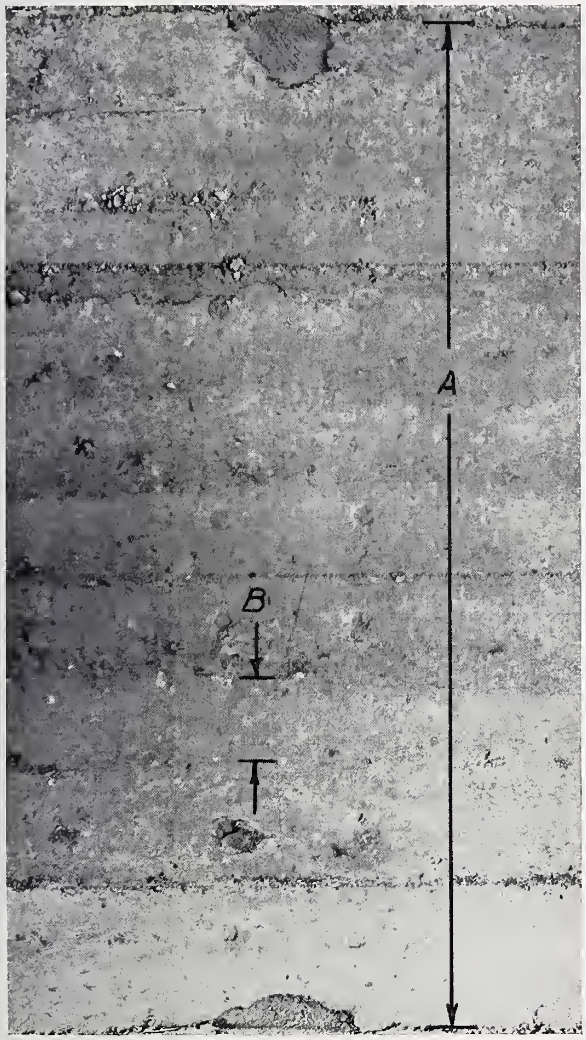

FIGURE 35.—*Texture of wall DD, monolithic terracrete.*
A, one course; *B*, one layer.

was spalling along a transverse line above midheight near one edge, and at 110 kips/ft additional spalling on the inside face near midheight. At the maximum load on specimens *C1* and *C2* there was more crushing and spalling. In specimen *C3* there was local crushing of one edge on the inside face at a load of 109 kips/ft. Under the maximum load there was crushing of the edges above midheight.

(*c*) *Transverse Load*

The results of the transverse tests on specimens *DD–T1*, *T2*, and *T3* are shown in table 10 and in figure 39.

Under a load of 48.6 lb/ft^2 on specimen *DD–T1* there was a transverse crack between two courses on the face not loaded, just above the upper loading roller. In specimen *T2* under a load of 62.3 lb/ft^2 a transverse crack appeared between layers at midheight on the face not loaded. In specimen *T3*, at a load of 110 lb/ft^2 there was a transverse crack between layers at midheight in the face not loaded. At a load of 120 lb/ft^2 a second crack between courses appeared in the same face and extended through the specimen at a load of 140 lb/ft^2. Under the maximum load on each specimen these cracks widened.

(*d*) *Concentrated Load*

The results of the concentrated tests on specimens *DD–P1*, *P2*, and *P3* are shown in table 10 and in figure 40.

After a load of 1,000 lb had been applied, the set in specimens *DD–P1* and *P3* was 0.004 in., and in *P2*, 0.011 in.

(*e*) *Impact Load*

Specimen *DD I3* during the impact test is shown in figure 41. The results of the impact loads on wall specimens *DD–I1*, *I2*, and *I3* are given in table 10 and in figure 42.

There was no failure of specimen *DD–I1;* after the 10-ft drop the set was 0.008 in. A transverse crack appeared at midheight in speciment *I2* between layers on the face not struck, and after a drop of 4.5 ft specimen *I2* ruptured transversely between two courses. At maximum height of drop the specimen completely separated. In specimen *I3* a transverse crack between two courses was observed on the face not struck after a drop of 1.0 ft. At a drop of 2.0 ft this crack extended through the wall, and at the maximum drop there was no bond between the two pieces of wall.

(*f*) *Racking Load*

The results of the racking tests on wall specimens *DD–R1*, *R2*, and *R3* are shown in table 10 and in figure 43.

After a load of 6.25 kips/ft had been applied, the set in specimens *DD–R1* and *R3* was 0.006 in./8 ft and in *R2* was 0.004 in./8 ft. No other effects were observed.

The price of this construction in Washington, D. C., as of July 1937, was $0.42/ft².

4. Terracrete-Block Wall *DE*

(*a*) *Description*

Wall *DE* was of machine-pressed terracrete blocks. The blocks were laid with cement-lime mortar. The block and mortar were exposed on both faces.

The full-sized terracrete blocks were 11⅞ by 10¼ by 8⅜ in. and weighed 82 lb as laid;

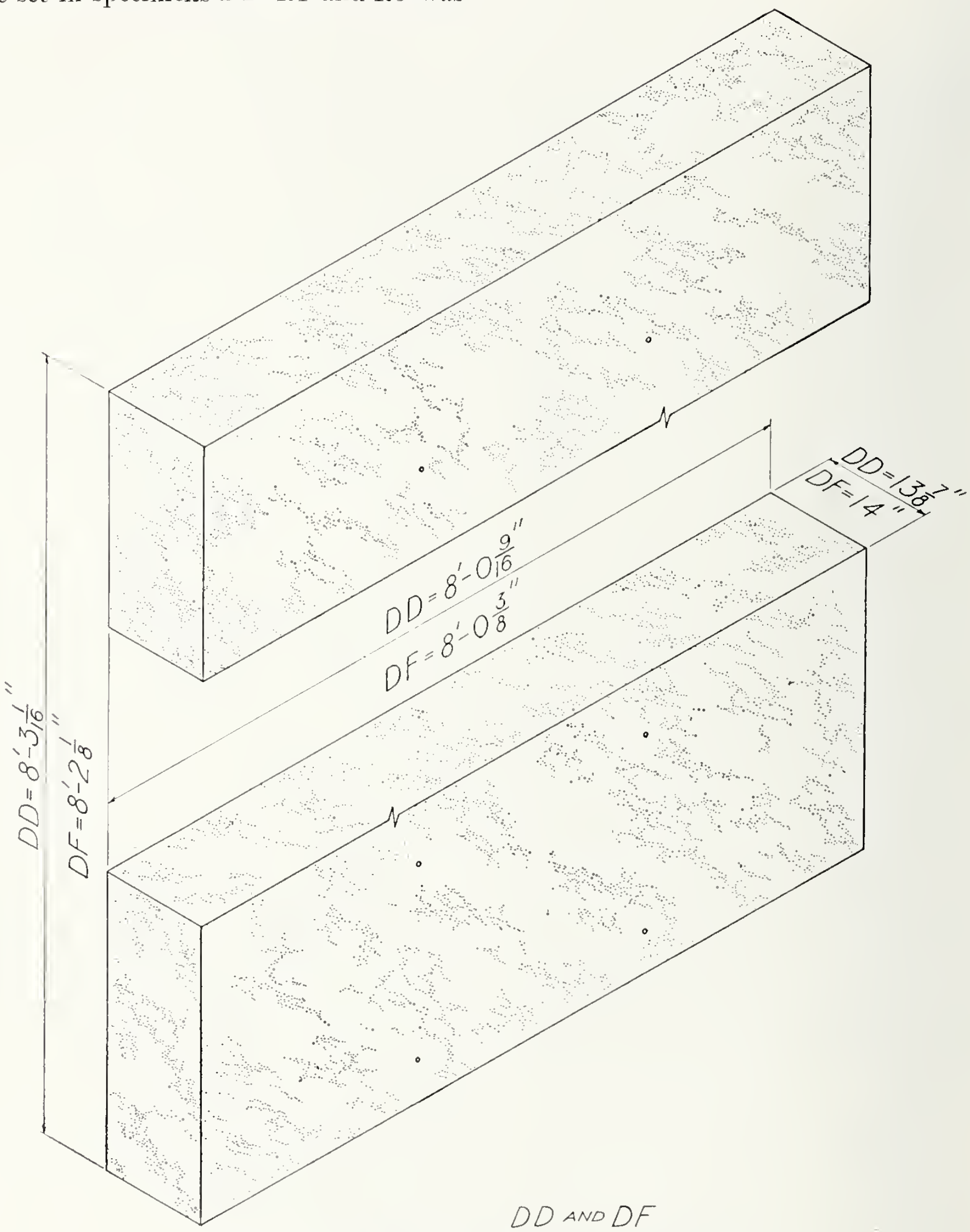

Figure 36.—*Eight-foot monolithic wall specimen.*

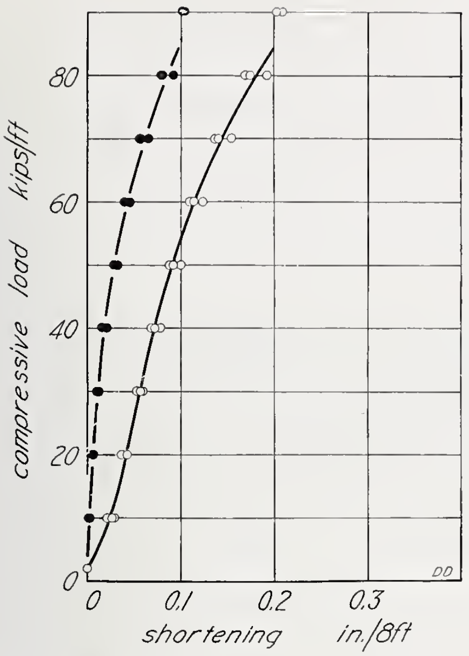

FIGURE 37.—*Compressive load on wall DD.*

Load-shortening (open circles) and load-set (solid circles) results for specimens *DD–C1, C2,* and *C3*. The load was applied 4.66 in. (one-third the thickness) from one face. The loads are in kips per foot of actual width of specimen.

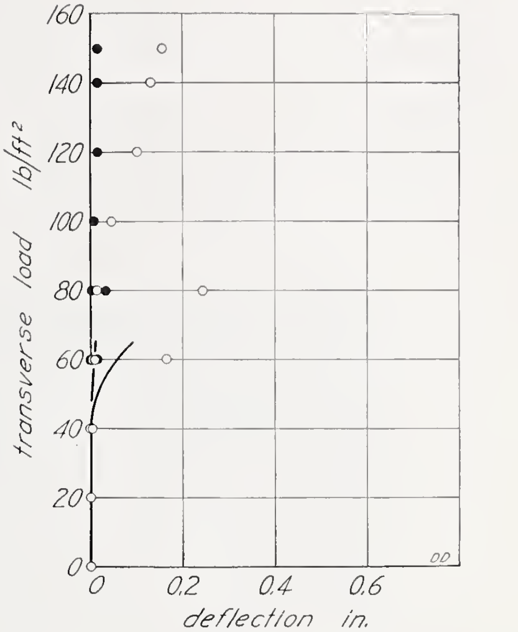

FIGURE 39.—*Transverse load on wall DD.*

Load-deflection (open circles) and load-set (solid circles) results for specimens *DD–T1, T2,* and *T3* on the span 7 ft. 6 in.

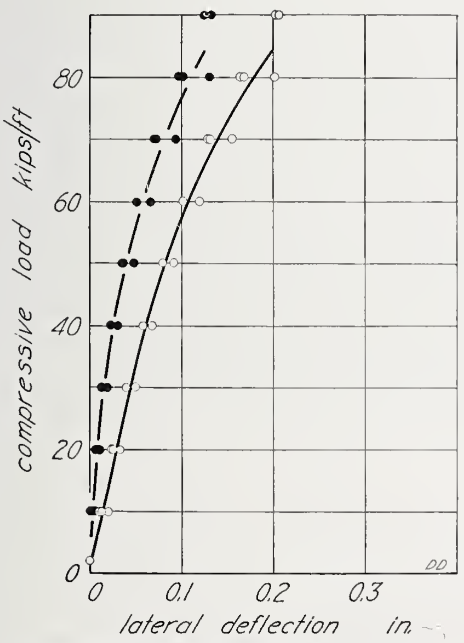

FIGURE 38.—*Compressive load on wall DD.*

Load-lateral deflection (open circles) and load-lateral set (solid circles) results for specimens *DD–C1, C2,* and *C3*. The load was applied 4.66 in. (one-third the thickness) from one face. The loads are in kips per foot of actual width of specimen. The deflections and sets are for a gage length of 7 ft. 6 in., the gage length of the deflectometer.

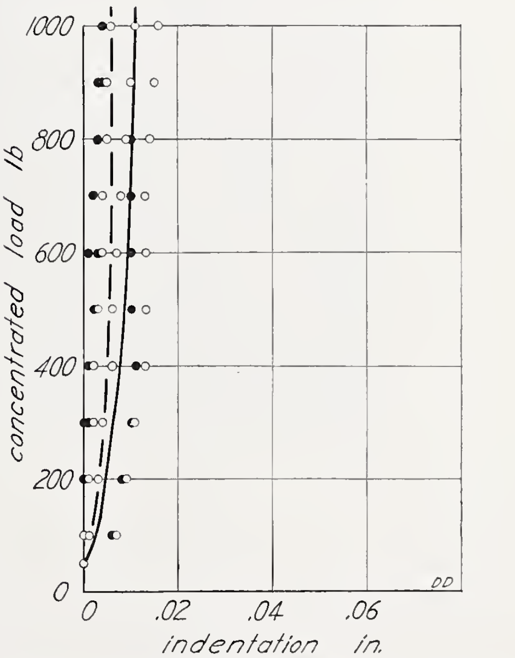

FIGURE 40.—*Concentrated load on wall DD.*

Load-indentation (open circles) and load-set (solid circles) for specimens *DD–P1, P2,* and *P3*.

the half-sized blocks were $11\frac{7}{8}$ by $4\frac{7}{8}$ by $8\frac{3}{8}$ in. and weighed 39 lb as laid. Both were pressed parallel to the $11\frac{7}{8}$ in. dimension. The full-sized and half-sized blocks are shown in figure 44.

The moisture content of the blocks as laid was 6.3 percent by dry weight. The modulus of rupture on the span of 10 in. (depth $10\frac{1}{4}$ in. and width $8\frac{3}{8}$ in.) was 180 lb/in². The were 8 ft 3 in. high, 3 ft $11\frac{3}{4}$ in. wide, and $11\frac{3}{4}$ in. thick. Each specimen was 11 courses high. The texture of the walls is shown in figure 46.

Eight-foot terracrete-block wall specimens.—The 8-ft wall specimens shown in figure 47 were similar to the 4-ft specimens. They were 8 ft $3\frac{1}{4}$ in. high, 7 ft $11\frac{1}{2}$ in. wide, and $11\frac{11}{16}$ in. thick.

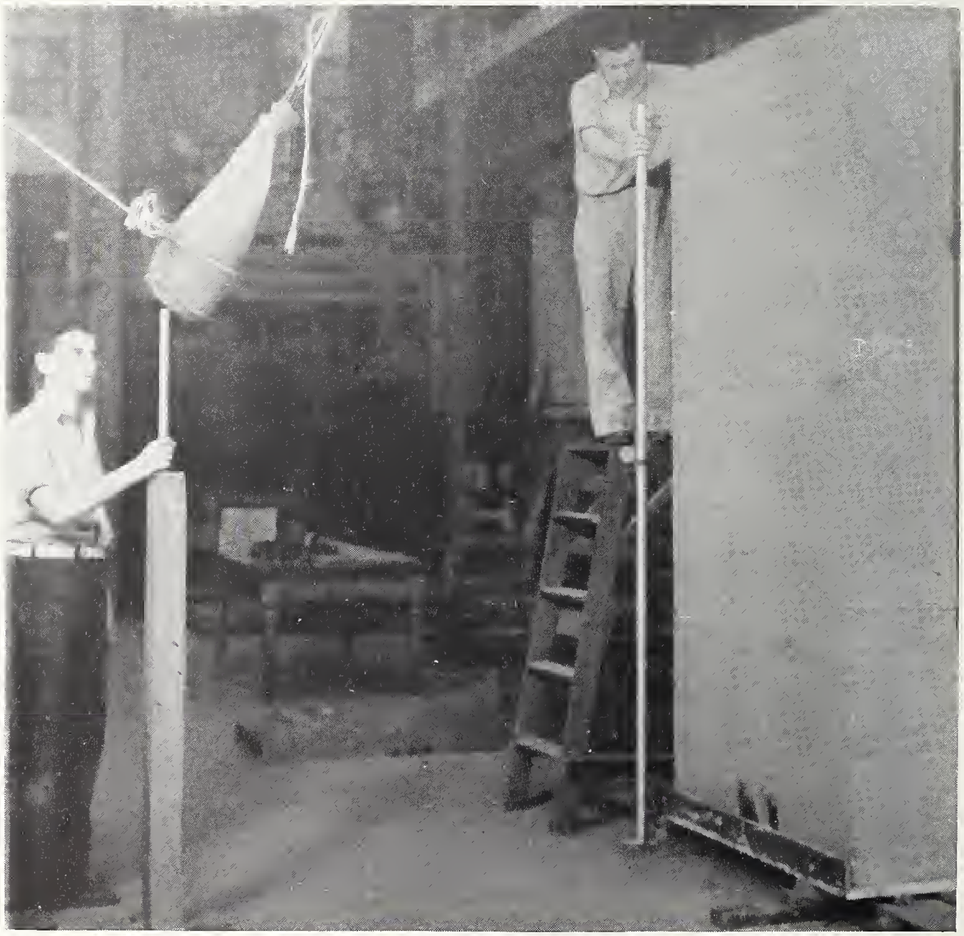

FIGURE 41.—*Wall specimen DD–I3 during the impact test.*

modulus of rupture on the span of 8 in. (depth $8\frac{3}{8}$ in. and width $11\frac{7}{8}$ in.) was 250 lb/in². The compressive strength of the full-sized blocks was 1,570 lb/in². The compressive load was applied to the $11\frac{7}{8}$ by $10\frac{1}{4}$-in. faces (horizontal when laid). The moisture absorption determined in accordance with ASTM C67–37 was 7.6 percent by weight.

Four-foot terracrete-block wall specimens.—The 4-ft wall specimens shown in figure 45

(b) *Compressive Load*

The results of the compressive tests on wall specimens *DE–C1*, *C2*, and *C3* are shown in table 10 and figures 48 and 49.

The shortenings and sets given in figure 48 are computed for a height of 8 ft. The gage length of the compressometers was 8 ft $3\frac{1}{4}$ in.

In specimen *C1* one edge on the inside face (the face nearer the load line) began to crush

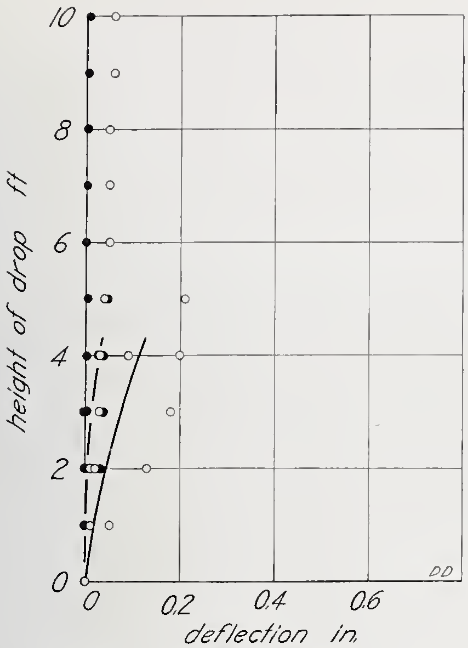

FIGURE 42.—*Impact load on wall DD.*

Height of drop-deflection (open circles) and height of drop-set (solid circles) results for specimens *DD–I1, I2,* and *I3* on the span 7 ft 6 in.

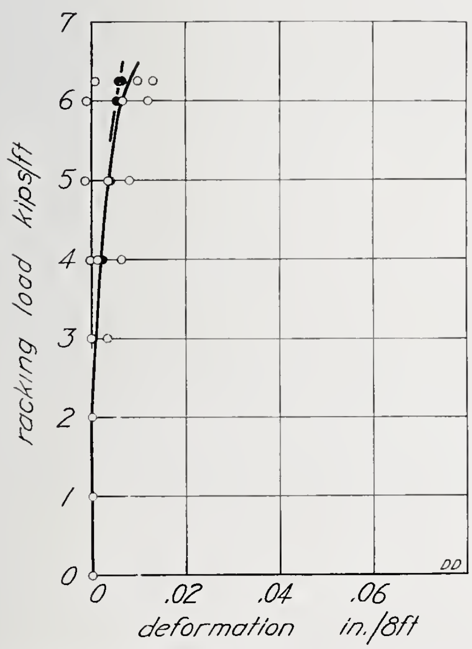

FIGURE 43.—*Racking load on wall DD.*

Load-deformation (open circles) and load-set (solid circles) results for specimens *DD–R1, R2,* and *R3.* The loads are in kips per foot of actual width of specimen.

near the top at a load of 116 kips/ft. Under the maximum load the specimen collapsed suddenly. In specimen *C2* under a load of 120 kips/ft vertical cracks appeared in several vertical mortar joints on the inside face near one edge of the specimen; under a load of 123 kips/ft there was crushing of the bed joints

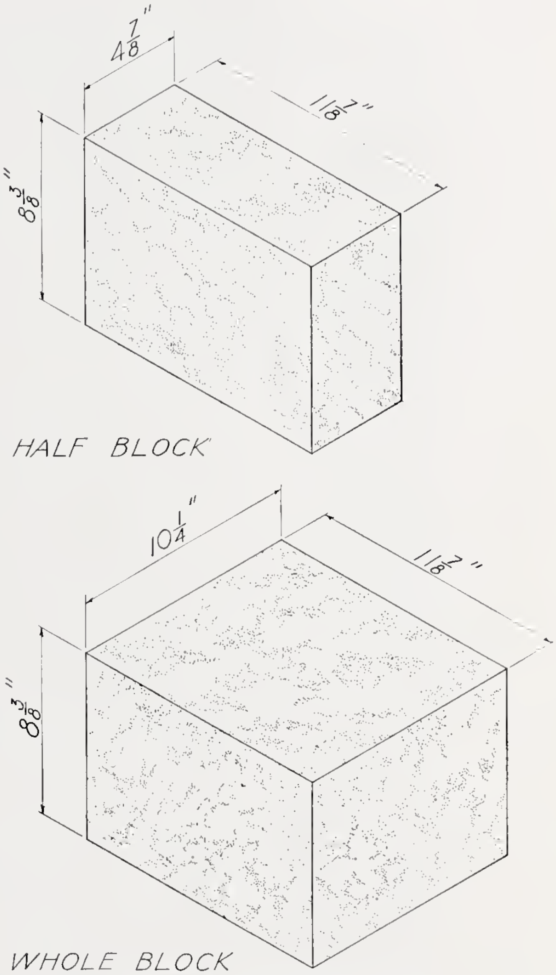

FIGURE 44.—*Terracrete block.*

Full and half size.

near the top on the inside face; under a load of 124 kips/ft the edge on the inside face crushed near the top of the specimen. In specimen *C3* a load of 105 kips/ft caused spalling at a vertical joint on the inside face near the top; at 108 kips/ft one edge began to crush on the inside face above midheight. Under the maximum load on specimens *C2* and *C3* the effects already mentioned were more pronounced.

(c) *Transverse Load*

The results of the transverse tests on wall specimens *DE–T1*, *T2*, and *T3* are shown in table 10 and in figure 50.

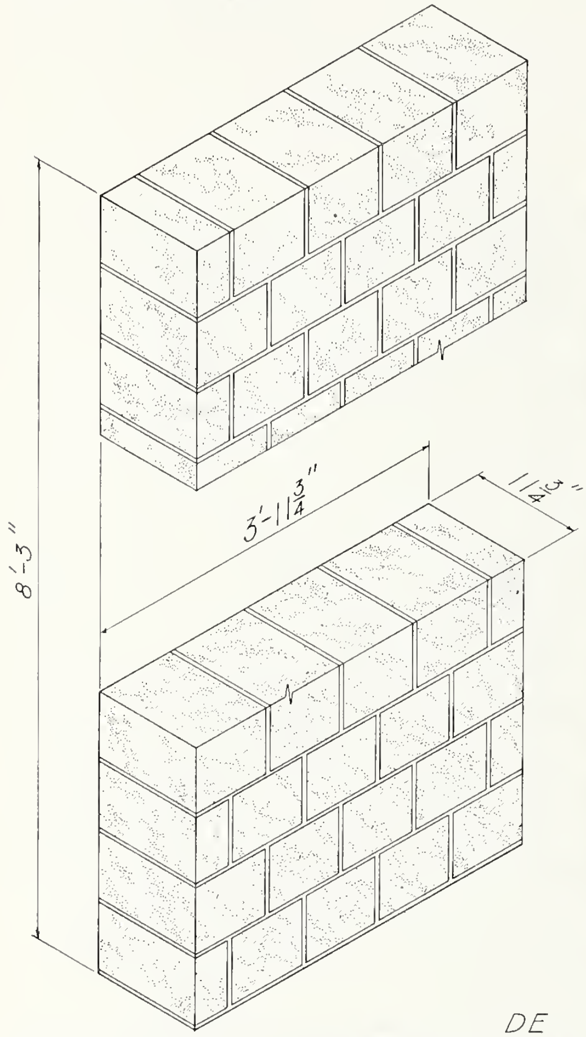

FIGURE 45.—*Four-foot wall specimen DE, terracrete block.*

Under the maximum load on each specimen the bond between the blocks and the mortar ruptured between the loading rollers.

(d) *Concentrated Load*

Wall specimen *DE–P3* under concentrated load is shown in figure 14. The results for the concentrated tests on specimens *DE–P1*, *P2*, and *P3* are shown in table 10 and figure 51.

After a load of 1,000 lb the set in specimens *DE–P1* and *P2* was 0.007 in.; and in *P3*, 0.000 in.

(e) *Impact Load*

The results of the impact tests on wall specimens *DE–I1*, *I2*, and *I3* are shown in table 10 and in figure 52.

In specimen *DE–I1* a transverse bond crack appeared near midheight in the face not struck after a drop of 4.5 ft; in specimen *I2* after a drop of 3.0 ft; and in specimen *I3* after a drop

FIGURE 46.—*Texture of wall DE, terracrete block.*

of 2.0 ft. This crack extended to the face struck after a drop of 6.0 ft in *I1*, 5.0 ft in *I2*, and 2.5 ft in *I3*. Under the maximum load each specimen was unstable when struck by the sand bag.

(f) *Racking Load*

Racking-test results on specimens *DE–R2* and *R3* are shown in table 10 and figure 53. The results for specimen *DE–R1* are not given because they indicated that this specimen had been damaged when it was alined in the racking frame. Evidently, forces had been exerted accidentally which caused transverse cracks not disclosed by visual inspection before the specimen was loaded.

Specimen *R1* and *R3* failed by rupture of the bed and head joints in stepwise cracks approximately along a diagonal from the point of load application to the stop. There was no failure of specimen *R2*.

The price of this construction in Washington, D. C., as of July 1937, was $0.36/ft².

One cylinder of damp earth was rammed in a mold, 8 in. in diameter and 8 in. high, for each specimen. The compressive strengths of the cylinders are given in table 13.

Four-foot rammed-earth wall specimens.—The 4-ft wall specimens, shown in figure 34.

FIGURE 47.—*Eight-foot wall specimen DE, terracrete block.*

5. RAMMED-EARTH WALL *DF*

(*a*) *Description*

Wall *DF* was an earth construction rammed by hand in wood forms. Each face was thin dagga plaster ("earth" and water).

were 8 ft 3$^{11}/_{16}$ in. high, 4 ft 0$^{1}/_{8}$ in. wide, and 1 ft 2 in. thick. The texture of the wall is shown in figure 54.

Eight-foot rammed-earth wall specimens.—The 8-ft wall specimens shown in figure 36 were similar to the 4-ft specimens. They were

8 ft $2\frac{1}{8}$ in. high, 8 ft $0\frac{3}{8}$ in. wide, and 1 ft 2 in. thick.

TABLE 13.—*Compressive strength of rammed-earth cylinders for wall DF*

[The compressive strength of the cylinders was determined by the Masonry Construction Section of the National Bureau of Standards on the day the corresponding wall specimens were tested]

Specimen	Compressive strength	Specimen	Compressive strength
	lb/in.²		*lb/in.²*
C1	270	*I2 (P2)*[a]	230
C2	260	*I3 (P3)*[a]	205
C3	235	*R1*	235
T1	215	*R2*	240
T2	190	*R3*	195
T3	185		
I1 (P1)[a]	190	Average	220

[a] The impact and concentrated loads were applied to the same specimens, the impact loads first.

(*b*) *Compressive Load*

The results of the compressive tests on wall specimens *DF–C1*, *C2*, and *C3* are shown in table 10 and in figures 55 and 56.

The shortenings and sets given in figure 55 are computed for a height of 8 ft. The gage length of the compressometers was 8 ft $3\frac{11}{16}$ in.

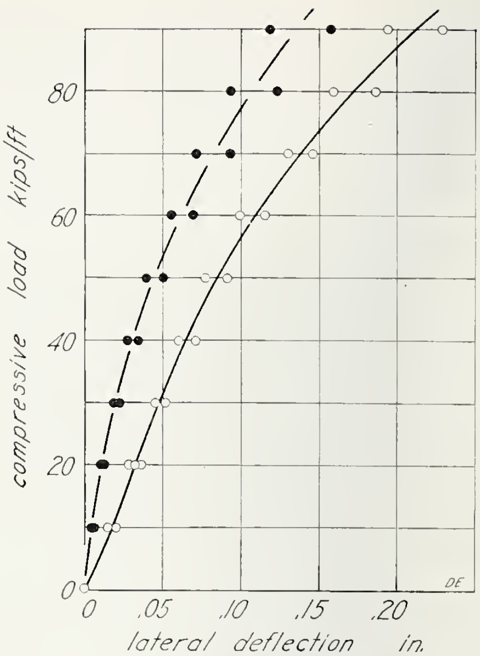

FIGURE 49.—*Compressive load on wall DE.*

Load-lateral deflection (open circles) and load-lateral set (solid circles) results for specimens *DE–C1*, *C2*, and *C3*. The load was applied 3.92 in. (one-third the thickness) from one face. The loads are in kips per foot of actual width of specimen. The deflections and sets are for a gage length of 7 ft 6 in., the gage length of the deflectometer.

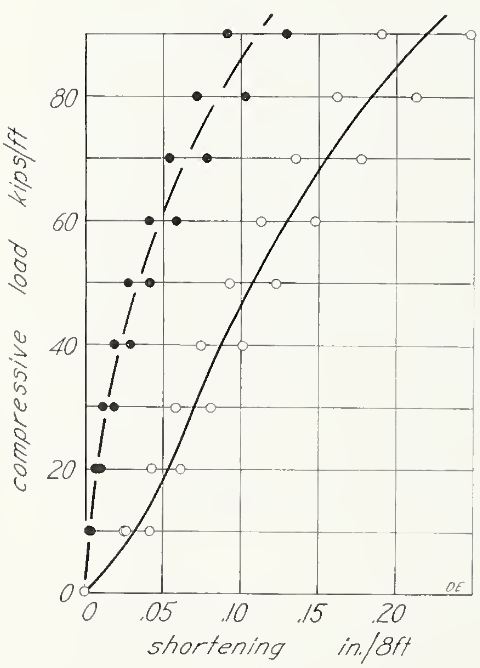

FIGURE 48.—*Compressive load on wall DE.*

Load-shortening (open circles) and load-set (solid circles) results for specimens *DE–C1*, *C2*, and *C3*. The load was applied 3.92 in. (one-third the thickness) from one face. The loads are in kips per foot of actual width of specimen.

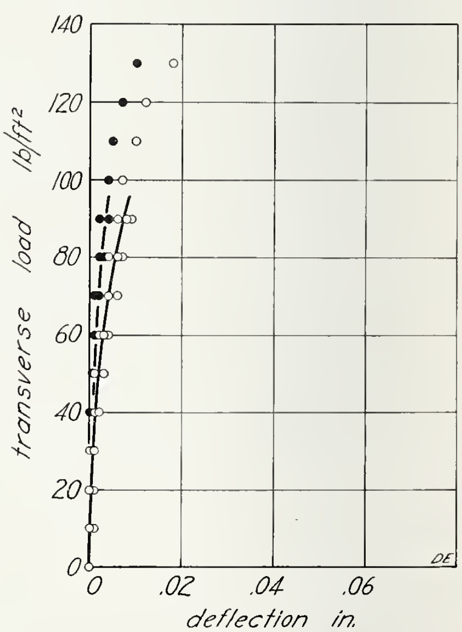

FIGURE 50.—*Transverse load on wall DE.*

Load-deflection (open circles) and load-set (solid circles) results for specimens *DE–T1*, *T2*, and *T3* on the span 7 ft 6 in.

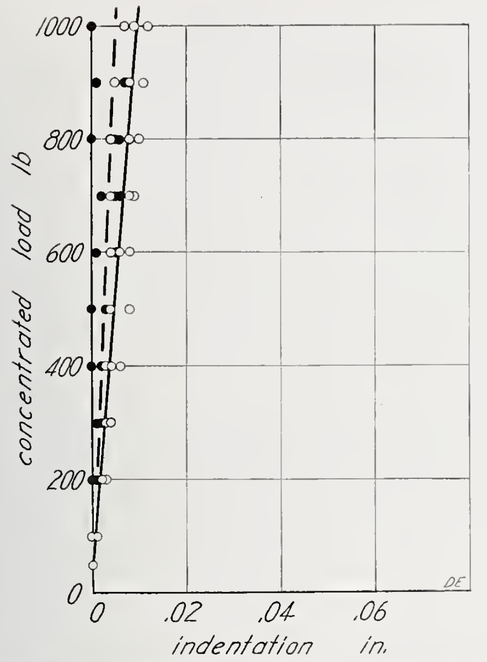

Figure 51.—*Concentrated load on wall DE, load applied to outside face.*

Load-indentation (open circles) and load-set (solid circles) results for specimens *DE–P1, P2,* and *P3.*

Under a load of 15.00 kips/ft on specimen *C1* the inside face spalled near the top. At 16.25 kips/ft, vertical cracks appeared in one edge of the specimen near the inside face close to the top.

Under a load of 10.00 kips/ft on specimen *C2*, vertical cracks appeared in both edges near the inside face at midheight. At 12.00 kips/ft the inside face spalled at midheight near one edge, and at 13.00 kips/ft there was spalling of the inside face at midheight. Under a load of 9.00 kips/ft, vertical cracks were observed near the top of specimen *C3* on the inside face near the corners. At 11.10 kips/ft the inside face spalled at midheight near the edge. Under the maximum load on each specimen the effects were more pronounced.

Specimen *DF–C2* after the compressive load is shown in figure 57.

(c) *Transverse Load*

The results of the transverse tests on specimens *DF–T1*, *T2*, and *T3* are shown in table 10 and figure 58.

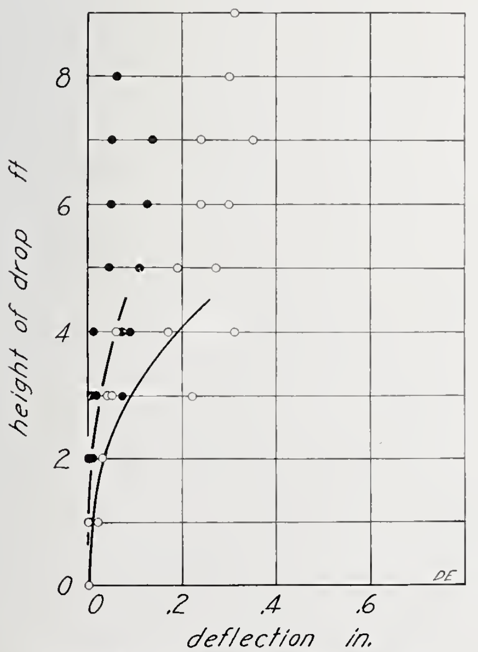

Figure 52.—*Impact load on wall DE.*

Height of drop-deflection (open circles) and height of drop-set (solid circles) results for specimens *DE–I1, I2,* and *I3* on the span 7 ft 6 in.

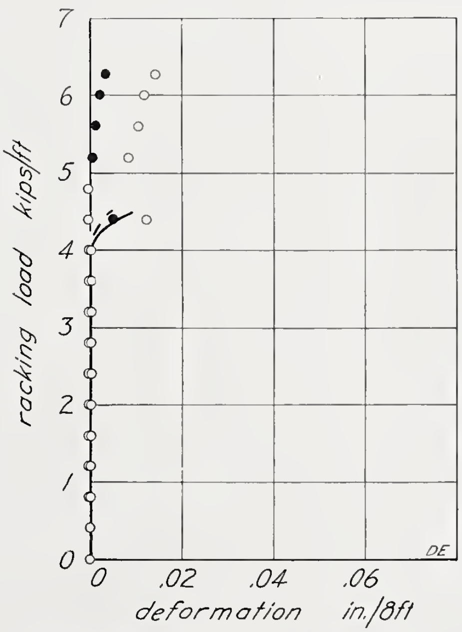

Figure 53.—*Racking load on wall DE.*

Load-deformation (open circles) and load-set (solid circles) results for specimens *DE–R2* and *R3.* The loads are in kips per foot of actual width of specimen.

Under the maximum load, specimens *T1* and *T2* ruptured transversely under a loading roller. Specimen *DF–T3* cracked transversely between a loading and a supporting roller at 48.8 lb/ft². The crack continued to widen until the maximum load was reached

(*d*) *Concentrated Load*

The results of the concentrated test on wall specimens *DF–P1*, *P2*, and *P3* are shown in table 10 and in figure 59.

The concentrated load was applied on one face near the center of the specimen. The indentation after a load of 1,000 lb was 0.126 in. for specimen *DF–P1*, 0.025 in. for *P2*, and 0.038 in. for *P3*. No other effects were observed.

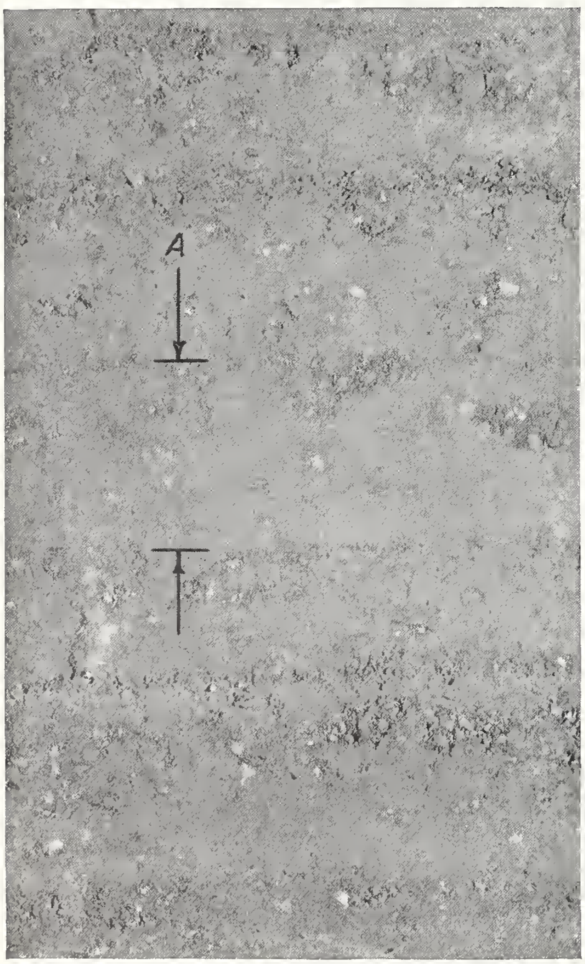

FIGURE 54.—*Texture o fwall DF, rammed earth.* *A*, one layer.

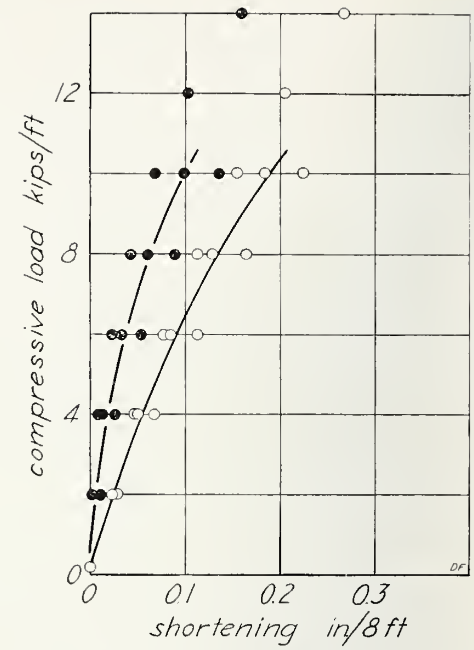

FIGURE 55.—*Compressive load on wall DF.*

Load-shortening (open circles) and load-set (solid circles) results for specimens *DF–C1*, *C2*, and *C3*. The load was applied 4.66 in. (one-third the thickness) from one face. The loads are in kips per foot of actual width of specimen.

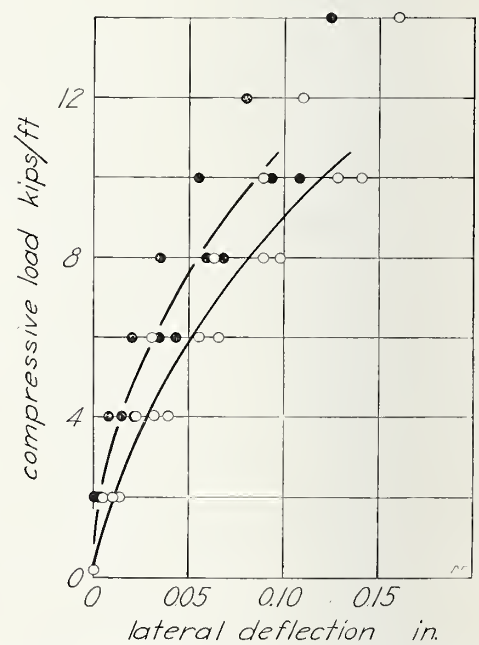

FIGURE 56.—*Compressive load on wall DF.*

Load-lateral deflection (open circles) and load-lateral set (solid circles) results for specimens *DF–C1*, *C2*, and *C3*. The load was applied 4.66 in. (one-third the thickness) from one face. The loads are in kips per foot of actual width of specimen. The deflections and sets are for a gage length of 7 ft. 6 in., the gage length of the deflectometer.

(*e*) *Impact Load*

The results of the impact tests on specimens *DF–I1*, *I2*, and *I3* are shown in table 10 and figure 60.

In specimen *I1* and *I2* after a drop of 1.5 ft a transverse crack was observed at mid-height in the face not struck, extending halfway into the wall. A similar crack appeared in *I3* after a drop of 2.0 ft. A second transverse crack above the first appeared in *I1* after a drop of 4.5 ft. In specimens *I1*, *I2*,

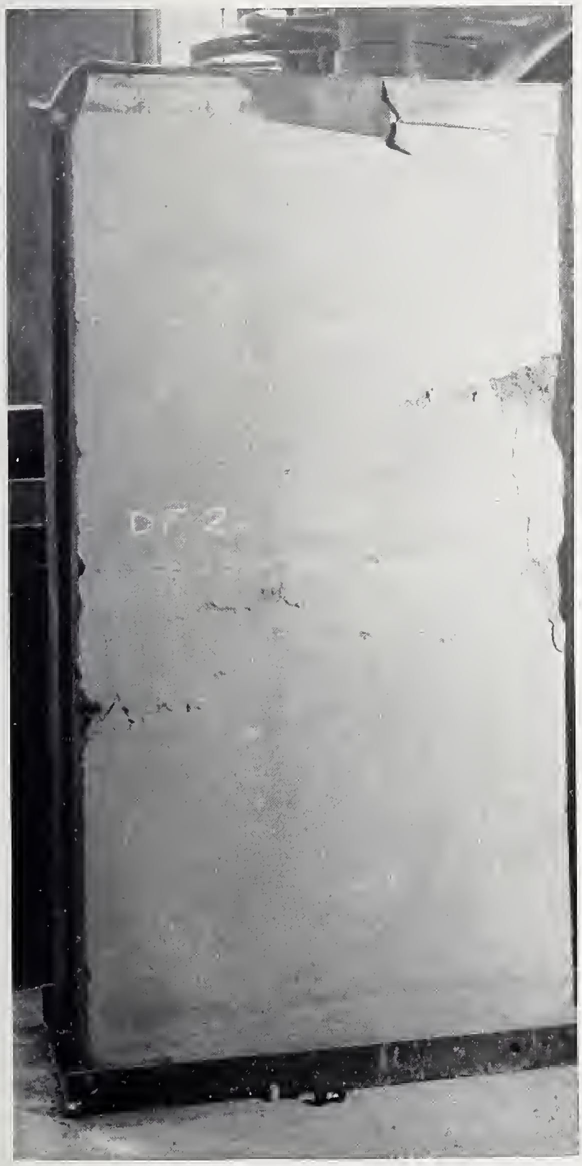

FIGURE 57.—*Wall specimen DF–C2 after compressive load.*

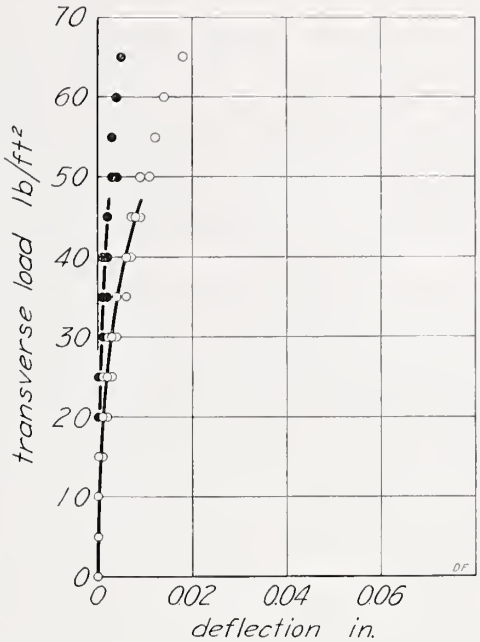

FIGURE 58.—*Transverse load on wall DF.*

Load-deflection (open circles) and load-set (solid circles) results for specimens *DF–T1*, *T2*, and *T3*, on the span 7 ft. 6 in.

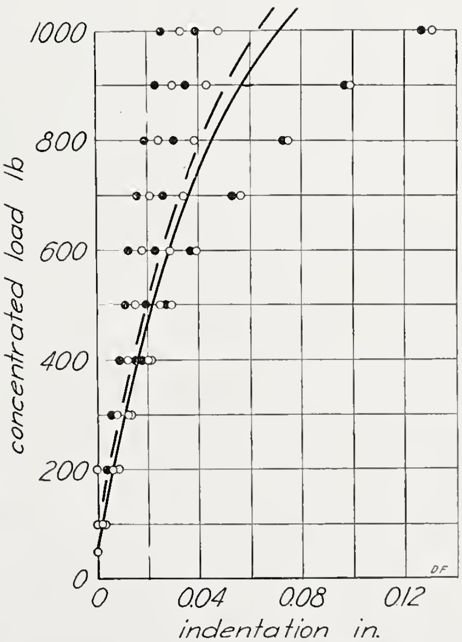

FIGURE 59.—*Concentrated load on wall DF.*

Load-indentation (open circles) and load-set (solid circles) results for specimens *DF–P1*, *P2*, and *P3*.

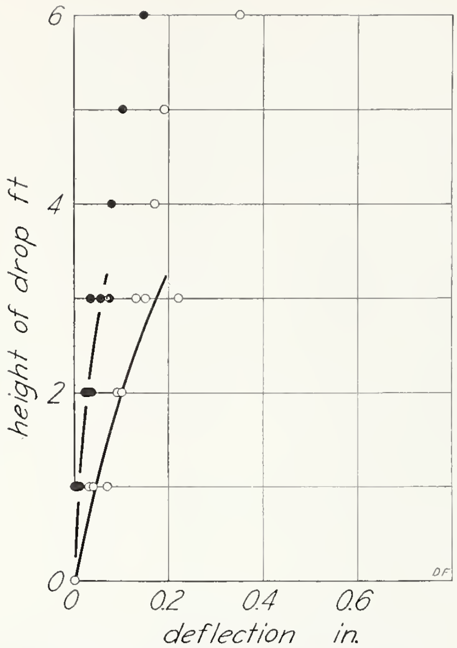

FIGURE 60.—*Impact load on wall DF.*

Height of drop-deflection (open circles) and height of drop-set (solid circles) results for specimens *DF–I1, I2,* and *I3* on the span 7 ft. 6 in.

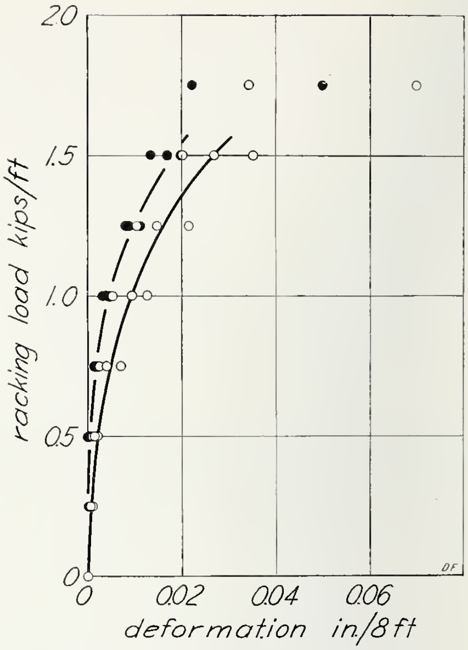

FIGURE 62.—*Racking load on wall DF.*

Load-deformation (open circles) and load-set (solid circles) results for specimens *DF–R1, R2,* and *R3.* The loads are in kips per foot of actual width of specimen.

FIGURE 61.—*Wall specimen DF–R3 under racking load.*

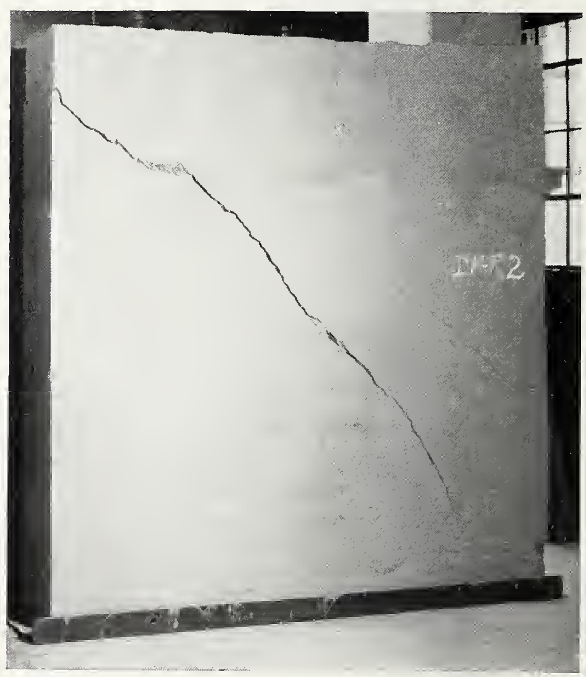

FIGURE 63.—*Wall specimen DF–R2 after racking load.*

and *13*, after drops of 7.0, 3.5, and 3.0 ft, respectively, the cracks extended through the wall. The tests were discontinued when the specimens deflected excessively under the impact loads.

(*f*) *Racking Load*

Wall specimen *DF–R3* under racking load is shown in figure 61. The results for the racking loads on specimens *DF–R1*, *R2*, and *R3* are shown in table 10 and figure 62.

In specimens *R1* and *R3*, the first cracks appeared under loads of 0.80 and 1.37 kips/ft, respectively. In each specimen the crack followed the horizontal joint between courses for about 3 ft from the loaded edge and then extended diagonally to the stop. Specimen *R1* cracked along a diagonal from the loading plate to the stop at a load of 1.75 kips/ft, and specimens *R2* and *R3* under the maximum load. Under the maximum load the crack in *R1* increased in width. Specimen *DF–R2* after the maximum load is shown in figure 63.

The price of this construction in Washington, D. C., as of July 1937, was $0.35/ft^2.

V. HEAT TRANSFER PROPERTIES

1. Specimens

Five specimens of earth walls were tested in a shielded hot-box heat-transfer apparatus. They were approximately 8 ft high by 5 ft wide and were of various thicknesses and compositions. They were allotted the laboratory identification symbols given in the following descriptions.

Specimen *HT13* was a monolithic terracrete wall 6 in. thick. The thermal transmittance was $U=0.79$, so that the heat loss through this wall would be comparable to that through a 6-in. monolithic concrete wall, such as No. 12A, in the 1940 "Guide" of the American Society of Heating and Ventilating Engineers. The conductivity, k, was 12 Btu/hr for each square foot and for each degree Fahrenheit per inch temperature gradient.

Specimen *HT14* was similar to *HT13* except for its thickness, 12⅛ in. The transmittance, U, was 0.64. Even though the walls were intended to be similar, the conductivity, k, of specimen *HT14* was 15.2 instead of the 12.0 for the preceding wall. In consideration of this difference, a small slab was cut from specimen *HT14* and tested for its conductivity in the Bureau's hot-plate apparatus No. 5. This apparatus requires specimens approximately 1 in. thick and 8 in. square. The actual measurement of heat flow occurs on an area 4 in. square.

This hot-plate test indicated a conductivity, $k=11.0$, which does not coincide with the results of the hot-box tests of either specimen *HT13* or specimen *HT14;* but the result is not considered conclusive, for two main reasons: First, the small slab prepared for the test was cut from the side of specimen *HT14*, not from the area through which the heat-flow measurement was made, and it does not follow that the composition of the small slab was representative of the entire specimen. Second, there is a possibility that the rough treatment necessarily accorded the small slab during its preparation loosened the stones and other components and resulted in the formation of openings or air pockets within it, with a consequent reduction in conductivity. The conductivity of walls of this class, however, is greatly dependent on composition, and differences as large as 4 parts in 15 are not surprising.

Specimen *HT15* was an adobe block wall 11¾ in. thick.

Specimen *HT16* was a bitudobe block wall 11¾ in. thick.

Specimen *HT18* was a monolithic rammed-earth wall, 12⅛ in. thick.

The results indicate that the heat transmittances of specimens *HT15*, *HT16*, and *HT18* were approximately equivalent to each other and that their conductivities are in the range expected for concrete.

In general, walls with great densities have high conductivities. The results of the heat-transfer determinations of earth walls agree in general with this relation.

2. Heat-Transfer Test Equipment

The heat-transfer tests were conducted in a shielded hot-box apparatus the arrangement of which is shown in figure 64.

During a test, heat flowed from the metering and shield boxes, which were heated electrically, to the cold box, which was cooled by a refrigerating machine. The electric energy supplied to the metering box was closely equivalent to the heat energy transferred through the area of the specimen covered by the metering box. The energy so supplied was measured with a watt-hour meter; and this measurement, converted into Btu and divided by the time, the area, and the temperature difference, yielded the heat-transfer coefficient for the specimen.

By means of the shield box, the space surrounding the metering box was maintained at substantially the same temperature as its interior except on the side in contact with the specimen. This minimized heat exchange to or from the metering box except through the specimen.

To promote uniformity of temperature, the air within the boxes was given a gentle motion by electric fans. The energy used by the fan in the metering box was added to that introduced by the heating coils to arrive at the total energy supplied.

Air and panel-surface temperatures were measured by copper-constantan thermocouples in conjunction with a potentiometer. Recording thermometers were used for approximate measurements of the interior temperatures of the boxes during the period preceding each test when the apparatus was being brought to a state of steady heat flow.

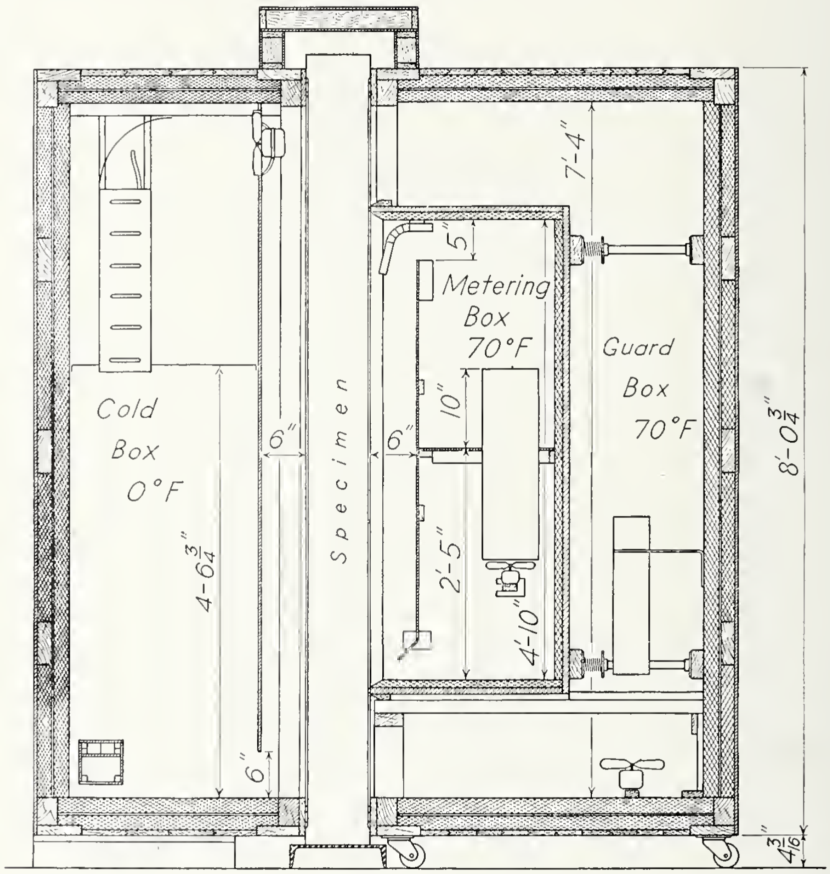

FIGURE 64.—Longitudinal Section Through Heat Transfer Apparatus

3. Heat-Transfer Test Procedure

For testing, each panel was placed in the apparatus in the position shown in figure 64, and the temperature in the cold box was adjusted as closely as possible to 0° F and that in the metering and shield boxes to 70° F. After a state of steady heat flow was attained, the heat transmission of the specimen, indicated by the rate at which electric energy was supplied to the metering box, was observed. The results of the observations are given in table 14.

TABLE 14.—*Heat-transfer coefficients and test data for earth wall specimens HT13, HT14, HT15, HT16, and HT18*

Item [a]	*HT13*, monolithic terracrete	*HT14*, monolithic terracrete	*HT15*, adobe block	*HT16*, bitudobe block	*HT18*, rammed earth
Density lb/ft³	130.0	130.0	100.0	100.0	125.0
Thickness in	6	12⅛	11¾	11¾	12⅛
Observed thermal transmittance, u	0.61	0.51	0.45	0.45	0.45
Corrected thermal transmittance, U	.79	.64	.54	.53	.54
Thermal conductance C	2.00	1.26	.91	.88	.93
Warm surface film conductance, fi	1.81	1.85	1.95	1.92	1.87
Cold surface film conductance, fo	1.73	1.64	1.65	1.72	1.59
Thermal conductivity, k	12.0	15.2	10.7	10.4	11.3
Temperature averages:					
Warm side:	° *F*	° *F*	° *F*	° *F*	° *F*
Air	69.9	69.9	70.2	70.3	70.1
Surface	46.2	50.4	53.8	53.9	53.3
Cold side:					
Air	−0.2	−0.4	−0.3	0.0	0.0
Surface	24.7	21.6	19.0	18.2	19.7
Temperature differences:					
Air to air	70.1	70.3	70.4	70.3	70.1
Surface to surface	21.5	28.8	34.8	35.7	33.6
Surface to air, warm side	23.8	19.5	16.3	16.4	16.8
Surface to air, cold side	24.9	22.0	19.3	18.3	19.7
Mean of air temperatures	34.9	34.8	35.0	35.2	35.1
Mean wall temperature	35.5	36.0	36.4	36.1	36.6

[a] The definitions of u, U, C, and k, representing the various coefficients of heat transmission, are:

u=number of Btu per hour transmitted through each square foot of specimen for each degree Fahrenheit difference in temperature between the air on the two sides, as observed under test conditions.

U=u corrected for a 15-mph wind outside and zero wind inside by means of the factors fi=1.65 and fo=6.00 taken from the ASHVE "Guide."

C=number of Btu per hour transmitted through each square foot of specimen for each degree Fahrenheit difference in temperature between the surfaces of the two sides as observed under test conditions.

k=The thermal conductivity of the material, which is equal to the conductance of a slab of homogeneous material 1 in. in thickness.

In this table, the heat transmission of the specimen is expressed in three ways. Two include the effect of surface coefficients and a third is independent of surface coefficients. The first result, the observed thermal transmittance, u, is the number of Btu per hour transmitted through each square foot of specimen for each degree Fahrenheit difference in temperature between the air on the two sides as observed for the conditions described under Heat-Transfer Test Equipment. Under these conditions the warm surface film conductance, fi, and the cold surface film conductance, fo, were those given in the table.

Since the air velocity and its effect on the two surfaces of the specimen may not be the same for different tests, it seemed desirable to correct the observed thermal transmittance to a standard condition of a 15-mph wind outside and zero wind inside. This was done to obtain the corrected thermal transmittance, U, by correcting the observed thermal transmittance, u, by means of the factors fi=1.65 and fo=6.00, as recommended in the ASHVE "Guide."

The thermal conductance, C, of the specimen also is presented, and this represents the number of Btu per hour transmitted through each square foot of specimen for each degree Fahrenheit difference in temperature between the surfaces of the two sides observed under the test conditions.

The thermal conductivity, k, is equal to the conductance of a slab of homogeneous material 1 in. in thickness.

4. Heat-Transfer Test Results

The results of the heat-transfer tests on five earth-wall constructions are given in table 14.

VI. WATER-PERMEABILITY PROPERTIES

1. Specimens

The specimens used for water-permeability tests were about 50 in. high, 42 in. wide, and of the same thickness as the corresponding structural specimens. They were supported on a single course of brick resting on a steel-channel section. The brick course contained a copper flashing so that water penetrating the specimen could be collected and the rate of flow measured. When laid, the bitudobe block absorbed little water from the mortar, whereas the adobe blocks were highly absorptive. The water content of the materials used in the specimens and both the consistency and the water retentivity of the mortars are given in table 15. The specimens were aged at least 1 month indoors before being tested.

TABLE 15.—*Construction data for earth walls*

Specimen No.	Type of wall	Thickness	Moisture content of material or block when wall was built	Mortar[1] Consistency (flow)	Mortar[1] Water retentivity
		In.	*Pct.*	*Pct.*	*Pct.*
B299 (DB)	Adobe block	12	3.9	102	78
B298 (DC)	Bitudobe block	12	1.6	89	79
B289 (DD)	Terracrete, monolithic	14	10.8		
B288 (DE)	Terracrete block	12	4.7	119	75
B286 (DF)	Rammed-earth, monolithic	14	9.6		

[1] Federal Specification for Cement, Masonry, SS-C-181b.

2. Water-Permeability Test Procedure

The water-permeability test is described, in BMS7, Water Permeability of Masonry Walls, as the "heavy rain test." The specimens were supported on metal skids and clamped into position so that the exposed face formed one side of a pressure chamber. An air pressure of 10 lb/ft^2 above atmospheric was maintained in the chamber, and water from a perforated tube was sprayed on the top of the exposed face at the rate of 40 gal/hr for 1 day, except where otherwise noted.

The following observations were made on the specimens during the test: Time for the appearance of moisture (dampness) and of visible water on the back of a specimen; time for the leakage of water from the flashing at the back of a specimen and the maximum rate of leakage; extent of damp area on the back at the end of 1 day. The ratings of performance in the water-permeability test are arbitrary and are based on the assumption that visible water, extensive damp areas on the back, or leakage through a wall would damage plaster applied directly to the wall or would injure the finished interior of a building. The following ratings have been devised for specimens that would not be damaged or eroded by the test exposure:

Good: No visible water on back of wall in 1 day. Less than 50 percent of the wall area damp in 1 day. No leaks through the wall.

Fair: Visible water on back of wall in more than 3 hr and less than 1 day. Rate of leakage, less than 1 liter/hr.

Poor: Visible water on back in 3 hr or less. Rate of leakage less than 5 liters/hr.

Very poor: Rate of leakage greater than 5 liters/hr.

3. Water-Permeability Test Results

Data obtained from the permeability tests are given in table 16.

TABLE 16.—*Permeability test data for earth walls*

Specimen No.	Type of wall	Time to failure as indicated by— Damp through wall	Visible water on back	Leak through wall	Maximum leakage per hour	Area damp on back in 1 day	Rating
		hr	*hr*	*hr*	*Liters*	*Pct.*	
B299 (DB)	Adobe block	0.03	0.03	0.02	2	([a])	VP.
B298 (DC)	Bitudobe block	4.00	18.00		0	13	F.
B289 (DD)	Terracrete, monolithic.	20.00			0	1	G.
B288 (DE)	Terracrete block	0.03	0.03	.4	0.05	65	P.
B286 (DF)	Rammed earth, monolithic.	([a])	([a])	([a])	0	([a])	VP.

[a] Duration of test 0.7 hr.

As can be noted from figures 65 and 66, the faces of both the rammed-earth and the adobe-block specimens were deeply eroded. The tests were stopped after an exposure period of 40 min because the drains were becoming clogged with material washed from the faces. There was no penetration of water through the rammed-earth specimen.

The monolithic terracrete specimen was found to be the least permeable. Moisture penetrated the terracrete at construction joints between layers of compacted material.

The specimen containing the water-repellent bitudobe block was less permeable than the specimen containing either adobe or terracrete block. Water penetrated all unit constructions only through the joints between the blocks and the mortar. The water permeability of these specimens appeared to be influenced by the water absorption of the blocks when laid.

Data from tests on brick masonry specimens made at the National Bureau of Standards subsequent to the publication of BMS7 indicate that a difference in the water absorption of brick at the time of laying had an important effect on the permeability after erection of otherwise similar specimens. It was found, as is indicated in the tests on earth-block specimens, that the lower the water absorption of the units when laid the lower the permeability of the specimens.

portland cement, are highly resistant to the penetration of moisture from wind-driven rains.

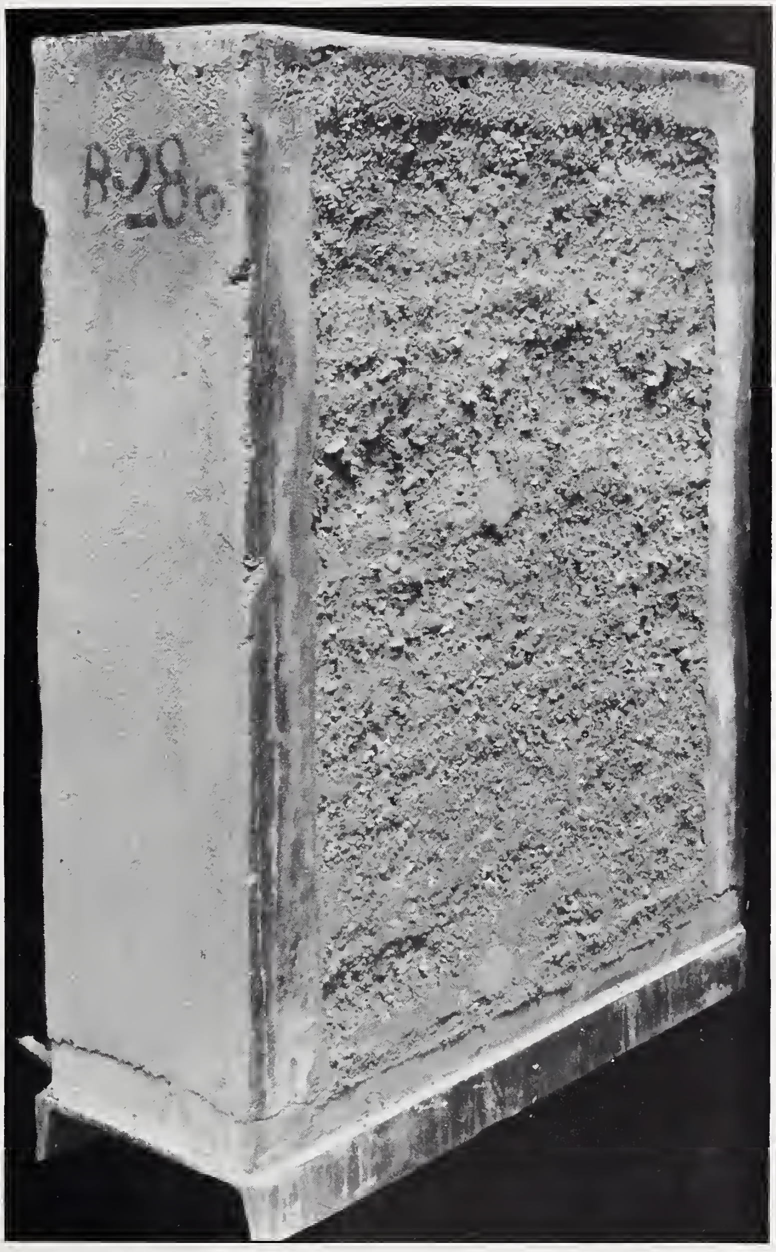

FIGURE 65.—*Rammed-earth water-permeability specimen after test.*

4. CONCLUSIONS

Walls of rammed earth or of adobe block require adequate surface treatment to protect them from the erosive effects of wind-driven rains.

Rammed-earth walls 14 in. thick, containing portland cement, are highly resistant to the penetration of moisture from wind-driven rains.

Walls of earth block, with or without admixtures of portland cement or emulsified asphalt, are permeable at the mortar joints to wind-driven rains. The degree of permeability increased with increase in the absorptive properties of the block at time of laying.

VII. ADDITIONAL COMMENTS

1. Types of Construction

Seven methods of earth construction are common in the United States. Adobe is most widely known; rammed earth is the strongest and most enduring of the nonstabilized types. These two methods indicate possibilities for improvement by applying modern methods and equipment for selecting, conditioning, and placing the earth. A brief description of the seven methods is given so that their relations to each other may be more evident.

(a) *Wattle and Daub*

Osiers and small poles are woven into a basket-like frame which is smeared and daubed with plastic earth, the operation being repeated until all contraction cracks resulting from drying are filled. This method, called "wattle and daub," is rather extensively practiced in the Southwest for skeleton walls of sheds or for lean-to additions to low-cost houses. While at best a primitive method, it provides the very poor of arid regions with a means of erecting inexpensive buildings. Its life depends on the type of soil, the care taken to

Figure 66.—*Adobe-block water-permeability specimen after test.*

exclude water, and the rigidity of the framework.

(*b*) *Sod Houses*

Lacking lumber for houses, the pioneers of the Great Plains resorted to the erection of sod walls. The heavy prairie vegetation produced a close-matted sod that was cut on the site into blocks 2 ft or more long, a foot or more wide, and 4 to 6 in. thick. These were laid like brick, with the grass side down; the length of the sod blocks determining the thickness of the wall. The roofs were relatively flat and of poles and slabs covered first with tar paper and then with two thicknesses of sod, grass side down. The interior surfaces were trimmed plumb and then plastered smooth with earth. Well-built "soddys" lasted from 10 to 20 years, depending on upkeep and on the dryness of the climate, a new roof being required occasionally.

While soddys were comfortable, they were at best makeshifts. This form of construction does not permit improvement of technique by applying newer building practices. However, sod could be piled against the walls of farm buildings and on roofs as protection against field fires.

(*c*) *Mud Walling*

In mud walling, earth of a plastic consistency is worked between studs of a frame building. Settlers in Pennsylvania utilized earth in this manner not only as a protection against cold winds but also as a safeguard from the flaming brands thrown by Indians in border clashes. It frequently was used for chinking log houses. The Mexicans in the Southwest build cajon walls (meaning "a narrow box") by erecting 2- by 4-in. studs, nailing lath to both sides, and filling in the enclosed space with stiff earth. Exterior walls built with occasional studs and filled with plastic earth and stone, sometimes lime, were at one time common in parts of Europe and have been known in this country. Temporary boards are fastened to the studs to facilitate filling, then are replaced with conventional wood siding. It is questionable whether this method has application except for interior partitions and for that portion of end walls protected by gables. Earth so employed has the advantages of occupying little space and providing insulation against sound and temperature.

(*d*) *Poured Earth*

In Martinsburg, W. Va., a house was built in 1887 by pouring thin earth mixtures between movable forms 6 to 12 in. high, and this method has been employed in other localities. The earth in each course is permitted to settle until sufficiently firm, when the forms are raised for successive courses. Excellent walls 12 to 18 in. thick are built in this way, but the method is slow and messy. Unless conditions are very favorable, contraction cracks are almost inevitable, when the wall dries, and must be filled with earth or mortar. Rocks 12 in. in diameter and smaller stones are sometimes imbedded in the wet earth. The poured-earth method of construction does not call for the heavy labor required for rammed earth and might become more common if asphaltic stabilizers were used to increase the weather resistance. The vacuum method for extracting moisture in concrete might be utilized to expedite consolidation and reduce shrinkage.

(*e*) *Monolithic Adobe*

The Indians and missionaries of the Southwest built monolithic walls of earth mixed with native grasses or charred twigs and water to the consistency of dough. This is the traditional method followed in England for building cob. The earth and straw are mixed by tramping it into a uniform mass. This adobe mixture is piled onto the wall in layers 6 to 24 in. high and 18 and 30 in. thick and left until sufficiently dry to bear the weight of succeeding layers. Earth that slumps beyond the wall lines in each course is cut plumb before adding other courses. Sometimes temporary boards support the earth. The exteriors frequently are plastered with the same earth mixtures or with lime mortar. Many old churches and other large buildings built by this method are still in use.

(*f*) *Adobe Block*

Adobe block, with or without straw or other bonding material, is the form of earth construction most widely found at present. While restricted to arid sections, other building materials are so scarce in these localities that adobe block fill a very definite need.

(*g*) *Rammed Earth*

Rammed earth and adobe block are the two basic forms of earth construction which are now being studied. Rammed earth has been built in monolithic and in block form, depending on preference, economy, and equipment at hand. More judgment than actual skill is required in working with rammed earth.

The technique should be mastered before the erection of a major building with monolithic walls is attempted. The difficulty of manipulating the heavy forms and the fact that mistakes of soil selection and ramming cannot be so readily detected as in block construction add to the problems of building monolithic walls.

Rammed earth is more durable than adobe and offers many opportunities for further development by the application of engineering methods.

2. Selection of Earth

Until recently the earth for construction merely consisted of a suitable material (sometimes vegetative binder or stones being added) mixed with water to obtain consistencies, varying from a slurry to one about the dryness of brown sugar, permitting pouring, molding, or ramming, depending on the method selected for building the wall.

Virtually the same kind of earth is suitable for all methods of building earth walls. Earth 12 to 18 in. below the surface is likely to be more uniform in composition and be freer of undesirable roots or humus (which should be avoided, especially for rammed earth) than surface earth. Contrary to popular belief, the earth must not have a high clay content; however, there must be a sufficient amount of clay (15 to 30 percent) to properly knit or bond the other ingredients. Unfortunately, "adobe" is a term applied to certain heavy clays and silty clay loams which contain much too high a percentage of clay to make satisfactory adobe block. These earths should not be confused with adobe construction.

For construction purposes, earth is classified mechanically by size of particles as sand, silt, and clay, and its suitability for structural use is then judged by the proportionate amounts of these materials. Very fine clay is colloidal in character; that is, it seems to have a gluelike or gelatinous property that readily takes up moisture—this is the material in soils that causes so much trouble due to its instability. When dry it absorbs a large amount of moisture and expands. Upon subsequent drying colloidal clay warps and contracts excessively, thereby causing cracks. Sand reduces shrinkage but excessive amounts of it prevent proper bonding. Too much silt produces a soft wall that erodes readily. When the earth contains an excess of clay, it can often be conditioned by adding sand; and sandy earths can be conditioned by adding clay. The best sand is one graduated between particles the size of a nut and fairly fine, as in concrete practice, so that the particles will interlock and be bound together with the colloidal material. However, too much large material is undesirable. The graduation of particle sizes in the earth described herein conveys a general idea of a well-graded soil.

3. Construction Equipment

Concrete mixers and pug mills are effective for mixing earth and water for earth constructions. The block press developed at the Haskell Institute and the pneumatic rammer serve to decrease the labor involved and to increase the rate of construction of rammed-earth and terracrete walls. Many rigging and scaffolding arrangements are advantageous when handling forms for monolithic constructions. Portable elevators of the kind used for loading coal trucks might prove practical for placing earth in forms, especially where duplication or mass production is practiced.

Builders who specialize in bitudobe, rammed earth, and terracrete could economically employ equipment. However, further experiments are needed.

4. Protection Against Moisture

Probably the outstanding weakness of earth walls is their susceptibility to damage by moisture. Moisture must be guarded against in any type of earth wall, for the wall will not last if water is absorbed. Moisture is absorbed by capillarity from the ground through a pervious foundation, by splashing, and from a leaking roof. Rains against a wall, however, damage it very little. Where the intervals between rains are not long enough to permit drying, especially in freezing weather, a waterproof coating is needed. Rivulets from the roof or rain gutters cut a plain-earth wall like a knife and are to be guarded against. Protection against erosion from sand driven by high wind is necessary in some regions.

The water-permeability tests indicate that the plain, or untreated, earth walls need a protective covering. The stabilized-earth specimens have sufficient resistance to moisture except in the case of faulty mortar joints.

Concrete, brick, or rubble-stone foundations, with a tar coating on top, or slate or asbestos shingles imbedded in mortar, prevent water rising by capillarity. Such protective foundations should be at least 12 in. above the surrounding ground level to prevent absorption of splashing water. Unless made of local stone laid by cheap labor, masonry foundations may prove expensive because they must be at least as thick as the earth walls. There is real need for studying the durability of stabilized-earth foundations and other economical types.

Little difficulty should be experienced in keeping the roof tight; and this should be done, for water is more insidious here than at the foundation. A sheet of tar paper laid in asphalt, slate imbedded in mortar, or a 6-in. concrete belt-course applied to the top of the wall afford fairly certain protection.

The cheapest coating is a wash that will not change the color of the walls when applied directly. Linseed oil so far appears to be the most promising. The next cheapest would be coatings similar to whitewash or calcimine. Rammed-earth buildings in Birmingham, Ala., have been coated with such preparations, some of which seem to be giving good results.

5. Construction Details

To build enduring earth walls is one thing; to build an earth house is another. Practices common to all masonry building should be understood and followed in addition to the technique of constructing earth walls.

Maximum economy is effected by carefully planning the order and details of construction and by selecting a design of simple lines with

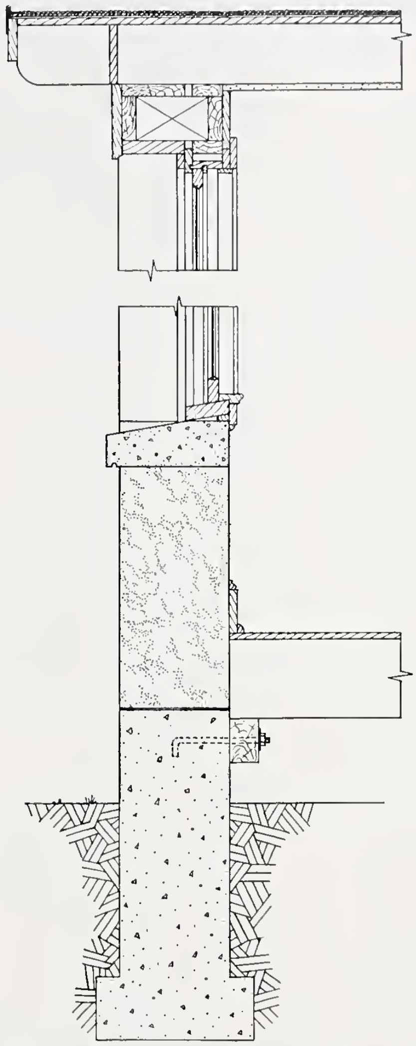

Figure 67.—*Typical details of monolithic wall, flat-roof construction.*

few angles. More than one story is structurally feasible by making the lower wall sections thick; however, the cost of building walls higher than one story is considerable.

Earth in the form of blocks presents fewer difficulties than monolithic walls because defective blocks can be discarded, suitable weather is not quite so vital during construction, window and door openings are not different from wall sections, and there are no heavy forms to manage. If there are few angles, openings, or protruding details, rammed earth and terracrete have advantages in being stronger and more enduring and often being lower in cost than other constructions.

More thought given to details is required for monolithic than for block walls. Where forms are used, a type should be selected that will be rigid and that can be easily handled. It is important to consider how the forms may be shifted, to reduce the number of resettings as much as possible. Considerable labor can be saved by making the wall sections between openings of uniform length so that a box-form may be used. Walls less than 14 in. thick are difficult to ram, although a thinner wall might have sufficient structural strength.

Window and door lintels must be strong when the earth is to be rammed over them. One good plan is to make the openings of such a height that the lintels come directly under the wall plate. The wall over lintels may be built of block if the high-lintel arrangement is not satisfactory.

Wide eaves and gables afford protection to the wall and are advisable if there is any doubt as to the permanence of the exterior coating. In adobe-block and other unit construction, a reinforced concrete cap continuous around the wall just under the plate is desirable.

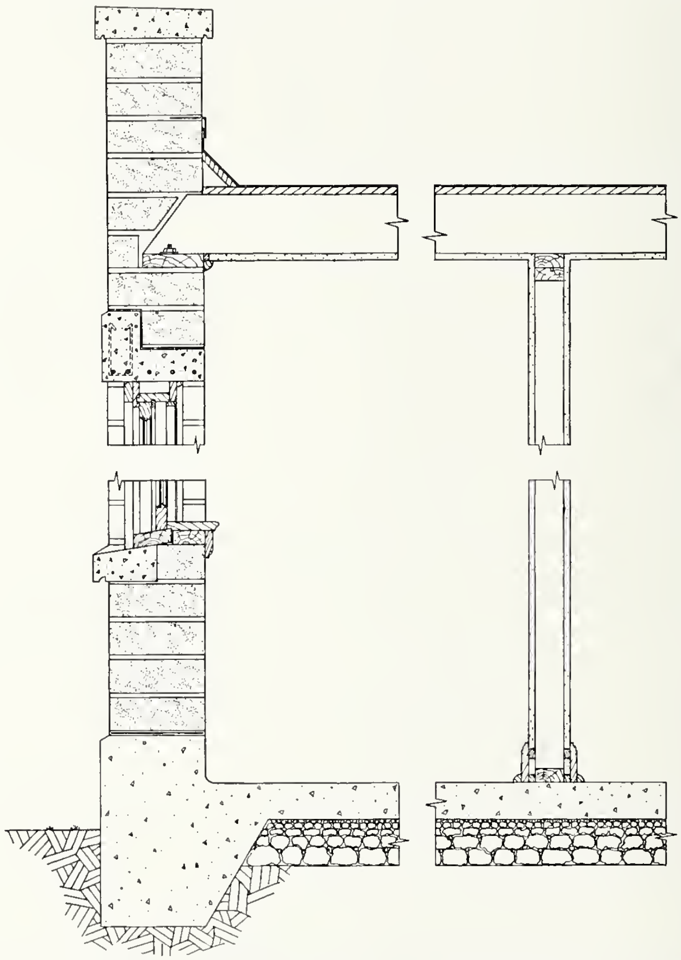

Figure 68.—*Typical details of block wall parapet-roof construction.*

Fireplaces and chimneys are commonly built of adobe block but must be lined with firebrick and flue lining. Except for the difficulty of ramming thin walls, fireplaces and chimneys

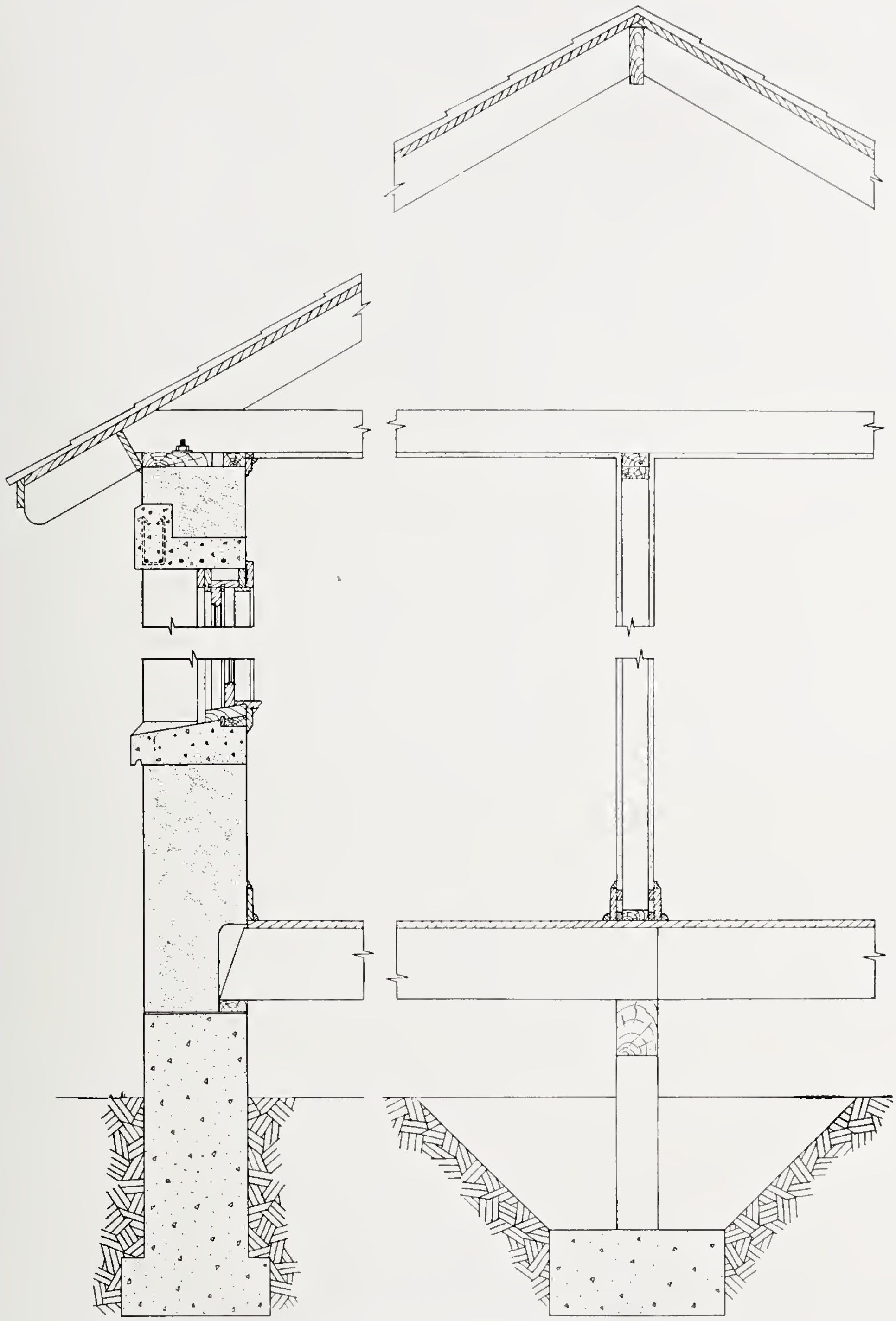

FIGURE 69.—*Typical details of monolithic wall, sloping-roof construction.*

FIGURE 70.—*Bitudobe-block house, typical Southwest architecture.*

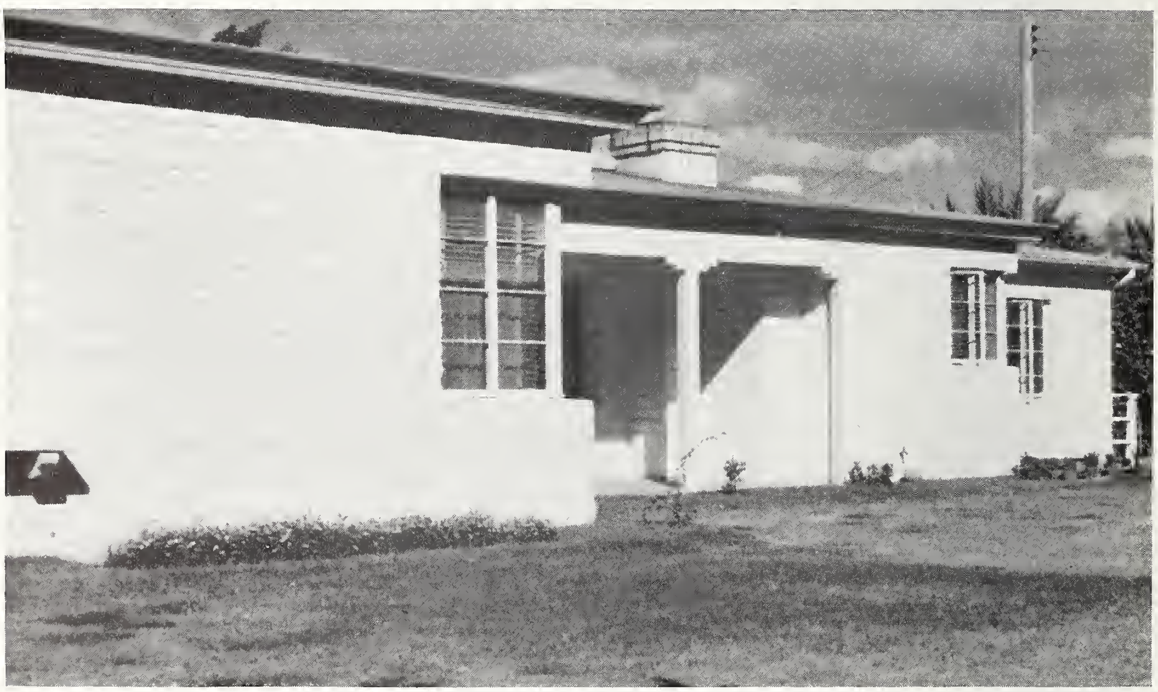

FIGURE 71.—*Bitudobe-block house, modern architecture.*

could be made of rammed earth or monolithic terracrete.

In the judgment of builders experienced in all types of earth construction, the typical details shown in figures 67, 68, and 69 represent satisfactory methods of construction.

The flat roof shown in figure 67 is a simple construction based on the practice of placing no solid wall above the lintel. A solid window sill is favored for a monolithic wall. The floor joists are carried on a wood support attached to the inside face of the concrete foundation. An impervious layer of tar paper is placed between the foundation and the wall.

The parapet roof shown in figure 68 is typical of the architectural style suitable to adobe or bitudobe construction. A continuous concrete cap protects the top course of block. The roof joists are supported on a wood plate inserted in the wall. The reinforced-concrete lintel is made sufficiently strong to support the wall above the window or door opening. A solid sill is not so essential in the block wall for offsets can be accommodated by fractions of block. The floor cast integrally with the foundation for the wall solves the floor-joist problem. An impervious layer of tar paper or slate imbedded in asphalt protects the wall from moisture in the foundation. A suitable nonloadbearing partition is indicated.

FIGURE 72.—*Interior view of bitudobe house, Southwest architecture.*

The sloping roof shown in figure 69 suggests the more conventional construction. Rafters and ceiling joists are supported on a wood plate. The reinforced concrete lintel and solid sill are recommended for the monolithic wall. The reinforced concrete lintel is especially necessary when any solid wall is carried over the window or door openings. Floor joists may be supported on a wood plate on the foundation. Material must be taken from the wall to allow the joists to bear on the plate; and this removal should be done as soon as practicable after the wall is started, for the wall soon becomes exceedingly hard. Tar paper or some other impervious material is placed on the foundation to protect the wall.

Two residences in Phoenix, Ariz., are shown in figures 70 and 71, illustrating respectively the typical Southwest architecture, with terracotta tile roof, and a modernly styled, shingled roof house. Bitudobe block laid in bitudobe mortar were employed in both houses.

Figure 72 presents an interior view of the house shown in figure 70. The exposed ceiling beams, rustic wall surface, and simple window openings are typical details of this construction. The walls can be plastered with either bitudobe or cement mortar.

The drawings of the specimens were prepared by E. J. Shell and G. W. Shaw of the Building Practice and Specifications Section of the National Bureau of Standards, under the supervision of V. B. Phelan.

The structural properties were determined by the Engineering Mechanics Section, under the supervision of H. L. Whittemore and A. H. Stang, and by the Masonry Construction Section, under the supervision of D. E. Parsons.

The chemical properties of the bituminous stabilizer were determined by the Paint Section, under the supervision of E. F. Hickson.

The heat-transfer properties of the constructions were determined by the Heat Transfer Section, under the supervision of M. S. Van Dusen.

The water-permeability properties were determined by the Masonry Construction Section, under the supervision of D. E. Parsons.

The following members of the professional staff assisted:

E. S. Cohen	W. G. Hoback	J. S. Rimmer
A. H. Easton	D. C. List	L. R. Sweetman
C. C. Fishburn	M. F. Peck	H. L. Weiss
A. Heiter	P. H. Petersen	

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WASHINGTON, June 11, 1941.

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