EARTHEN HOME CONSTRUCTION

A Field and Library Compilation With an Annotated Bibliography

By

LYLE A. WOLFSKILL

WAYNE A. DUNLAP

and

BOB M. GALLAWAY

TEXAS TRANSPORTATION INSTITUTE

Bulletin No. 18

E 18-62

This report was prepared for the Agency for International Development under the technical supervision of the Office of International Housing Housing and Home Finance Agency

TEXAS TRANSPORTATION INSTITUTE

(A Part of the A. & M. College of Texas)

College Station, Texas

We are sorry but some of the older reports are AS IS.

The pictures are of poor quality.

ACKNOWLEDGMENT

The authors would like to acknowledge those who prepared the original references from which this material was obtained. The many agencies and people involved make it impossible to acknowledge all of them separately.

The important contribution of Mr. J. Robert Dodge, Director, Division of Technical Service and Documentation, Office of International Housing, Housing and Home Finance Agency, and Mr. Richard C. Knight, Chief, Housing Division, Europe, Africa Bureau, Agency for International Development, in the form of reports, films, and personal experiences, cannot be overlooked.

It would be remiss if the names of Mr. Leon Watson and Mr. Robert Koeber, contractors and builders of adobe homes in Albuquerque, New Mexico, remained unmentioned. These two gentlemen unselfishly provided important information gained from their wide experience with adobe construction.

Mr. Razaur Rahman, exchange student from Pakistan, assisted in locating and extracting information from many of the references. The authors' sincere appreciation goes to Mrs. Georgia Ptacek and Mrs. Kay Barnfield for their diligent typing and preparation of the original manuscript.

TABLE OF CONTENTS

EARTHEN HOME CONSTRUCTION

INTRODUCTION

Earth represents the most prevalent and probably the oldest construction material known to man. Undoubtedly, earth was the principal material used for shelter when man emerged from caves. Through the centuries, these earth shelters have evolved from the primitive pole frames plastered with mud to the modern and beautiful adobe and rammed earth houses that can now be seen in the Southwestern United States of America and other parts of the world.

In some areas, earth structures built centuries ago are still in excellent condition, but in other areas where soil types and climatic conditions are less favorable, plain earth structures are short-lived and, at best, require continuous maintenance. As a result, earth, although economical and plentiful, has largely been replaced by more expensive materials of greater durability.

The rapid development of soil mechanics in the 20th century has resulted in means of adequately predicting the behavior of soils. Research and experience—primarily in the road-building industry—have shown that oftentimes the undesirable properties of soils can be altered by the addition of selected stabilizing agents. The net results of this continuing growth of knowledge concerning soils is the feeling that suitable earth houses can be constructed by proper soil selection and/or application of the proper soil stabilizer. Due, however, to the lack of dissemination of this new-found soils knowledge, the impact of these discoveries has had little effect on the ill-housed people of the world. The prejudices against earth-housing have taken deeper roots and have become more widespread as an increasing number of earth houses have failed.

In recent years, the International Cooperation Administration (now the Agency for International Development) has provided technical assistance and, in some cases, limited financial aid for demonstration projects in low-cost dwelling construction in less industrialized countries. Many of these projects employ the aided self-help approach and are intended to demonstrate the feasibility of people building their own homes with their own labor but with appropriate types of aid, including loans for building materials, and technical guidance in group organization, and building.

These projects emphasize the utilization of appropriate indigenous building materials and the advantages of using earth for houses in many countries has been recognized. However, information on modern soil mechanics has been somewhat fragmentary and often not presented in such a way as to be most useful to technical advisors and others responsible for supervising construction. As a result, the International Cooperation Administration authorized a research project by the Texas A. & M. Research Foundation, College Station, Texas, for the purpose of (1) collecting and analyzing the available information on earth housing, (2) performing research in areas of limited knowledge, and (3) bringing this information together in a simple 'primer' for easy utilization by the people planning, supervising, and constructing earth homes. The first and perhaps the most important phase of this research consisted of a complete survey of the available information concerning earth housing.

In the course of the library research, information was found to be scattered in technical reports from many nations, in periodicals and magazines, and even in newspapers. More than 300 references were read, and important information was obtained from many of them. The difficult and time-consuming process of locating, reading, and abstracting this information suggested to the authors that it should be made available to keep others from duplicating this effort. It is for this reason that this text was offered for publication. It is recommended, however, that the serious reader consult the original references, too, to obtain the context and additional supporting facts.

This bulletin divides the general subject of earth houses into several different categories and briefly reports the information that is available in each category with references to the original publications. No attempt has been made to analyze the voluminous data that are available.

The bibliography at the end of this bulletin is divided into two portions. The primary bibliography refers to articles and reports that are considered to be most authoritative or pertinent. Publications of lesser importance or of repetitious information from the primary bibliography are contained in the secondary bibliography. Some films viewed during the research are also listed.

It is anticipated that this information will be of interest primarily to the research-minded person who contemplates further investigations in the field of earth housing. Additionally, private individuals who are interested in constructing residences, camps, animal shelters, etc., may find this bibliography helpful.

Every attempt has been made to extract accurately information and data from the various articles and to give proper credit to writers and reporters for the vast amount of work that has been published.

TYPES OF EARTH CONSTRUCTION

General

As a result of the varying climates, soils, and building technologies throughout the world, several types of earth wall construction have been developed. Regardless of the method used, the builder realizes the advantages of constructing his own home with little assistance and at a cost he can afford.

In its simplest form, wetted earth is molded by hand into the shape of a wall either by the cob

Figure 1. This livable home, built by Leon Watson and Associates, in Albuquerque, New Mexico, demonstrates the quality and natural beauty of adobe architecture of the Southwestern United States.

method or the wattle and daub method. The cajon method is used in some areas where timber is available for framework. Wooden forms can be used to control the shape of the molded earth, as in the adobe method. In areas of advanced building technology, larger forms have been used so that walls can be built in-place monolithically. Since the earth can be rammed or compacted in these forms, the advantages of higher strength and better stability are realized. In recent years, through the cooperative efforts of industry, research stations, and government self-help programs, machines have been developed that will manufacture sufficient earth blocks to construct multi-unit projects. These mass-produced blocks have incorporated proven stabilizing agents to produce high strength, weather resistant earth walls.

Brief descriptions and relative advantages and disadvantages of several methods of construction are discussed below. The general topics of soil information and detailed construction practices as related to each individual method will be discussed later in the bulletin.

Cob

"The English cob method of construction requires a stiff mud, which is piled up in relatively thick layers to form the wall directly, without the use of shuttering (forms). The mud must be mixed to a heavy enough consistency so that it will have little tendency to slump. If a certain amount of slump or spreading occurs, the mud is put back in place with a trowel, or the edge is sliced off and placed on top. Shrinkage cracks in this type of construction may often cause serious trouble."[96*] The primary advantage in this method is simplicity in technique and construction equipment.

Figure 2. The right half of this residence in Greece shows the wattle in place. Daub will follow.

Wattle and Daub

"In the wattle and daub method of earth construction a framework of posts and poles is built up into which is woven or fastened reeds or rods to form a base for mud plastering. The plaster, at the proper consistency for easy working, is applied to both sides of the framework. Shrinkage cracks in the thin wall are common. A somewhat similar construction consists of a double wall of poles and withes filled with mud. Almost constant maintenance is to be expected with these types of construction."[30] The required maintenance becomes more difficult to accomplish as the occupants become less active due to old age or sickness. Consequently, this type of construction may fail to give adequate shelter at a time when the occupants sorely need the protection. This method is usually impractical in arid areas where the meager supply of brushwood must be used for fuel. An example of wattle and daub type of construction is shown in Figure 2.

Cajon

Cajon is a Spanish name referring to earth wall construction in which a clayey soil mix of appropriate consistency is used in the form of wall panels supported by a structural wall frame of either timber or concrete. Essentially, the advantage of the earth is that it eliminates timber sheathing.

Adobe Blocks

Walls of adobe blocks represent one of the most popular types of earth construction. The blocks are manufactured by placing mud of suitable consistency in forms and then curing the blocks prior to placing them in the wall. Since shrinkage occurs during the curing period, this procedure allows the use of soils with higher clay contents than the preceding methods or the rammed earth method. Traditionally, adobe blocks have been stabilized with straw although more effective admixtures are available for modern construction.

This method requires more labor than any of the other techniques, since the blocks must be handled during manufacturing, curing, and placement in the wall; however, satisfactory crack-free walls result. A distinct advantage is that part-time labor can be used to make the required quantity of blocks before actual fabrication of the building.

Poured Adobe

To reduce the labor requirement of adobe blocks, the prepared earth in the consistency of a plastic mud may be poured into forms to build the wall monolithically. Shrinkage cracks normally occur which must be grouted with mud plaster. This method appears to be of minor importance and it will not be discussed further in this publication.

*Superior numbers refer to references in the bibliography.

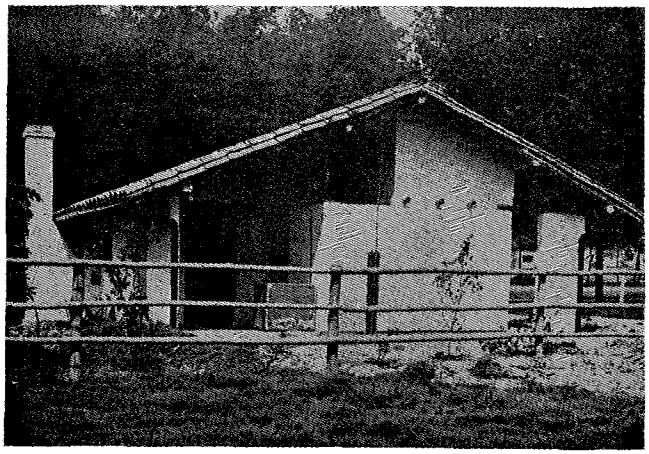


Figure 3. Machine-made block house.

Rammed Earth

In the rammed earth method of construction, walls are built with moist sandy loam, which is tamped or rammed into position between heavy formwork. Either hand or pneumatic tampers can be used. Careful selection of the soil type is necessary to prevent shrinkage, and the moisture content must be closely controlled to allow proper compaction. The finished wall can be stuccoed or painted if desired to produce a durable and pleasing finish.

Although the construction equipment requirements are greater than for the preceding methods, a large saving in labor is effected.

Machine-Made Blocks

The recent introduction of block-making machines has contributed to renewed interest in earth house construction. Such block-making machines have high production rates and the mechanically compressed blocks which they produce combine the high density and strength characteristics of rammed earth with the construction ease and crack-free walls of adobe blocks. Soil stabilizers can be readily incorporated in the blocks eliminating—in many cases—the need for protective coverings such as stuccoes or paints. The performance of the stabilized blocks compares favorably with burnt brick, lumber, and other conventional building materials.

Figure 3 illustrates a rural dwelling constructed of machine-made blocks.

SOIL CHARACTERISTICS AND CRITERIA

To predict the suitability of any soil for a particular construction method, it is necessary to evaluate certain characteristics and physical constants of the soil. Based on past experience, many methods that approximate standards have been devised and these may serve as a guide for the potential builder. In cases where suitable standards have not yet been devised, the builder will have to exercise his judgment considering such factors as financial resources in the project, experience of others in the locality, and availability and caliber of soil testing facilities. This section will cover the usual soil characteristics and physical constants and then discuss their relationship to each construction method.

Characteristics and Physical Constants

Gradation

Soil grains exist in a variety of sizes from colloidal particles less than 0.001 mm up to maximum gravel sizes of 3 inches. Normally, the grain sizes are grouped into four main categories: gravel, sand, silt, and clay; but various soil classification systems place the boundaries between categories at different sizes. These variations in grain size boundaries are illustrated in Figure 4.

For earth house purposes, most authors consider only two divisions of the soil—sand and clay. In this case, the "clay" part includes silt so that "fines" would be a more nearly accurate term. Similarly, "sand" includes gravel and actually represents the "coarse" part. These two terms, the coarse fraction and the fines, embrace all of the soil constituents. The dividing line is between coarse silt and fine sand. Many authorities feel this simpler division will suffice except for laboratory research studies. Fitzmaurice[36] however, disagrees that the simple sand-clay ratio is sufficient for design where competent engineering services are being used on the project.

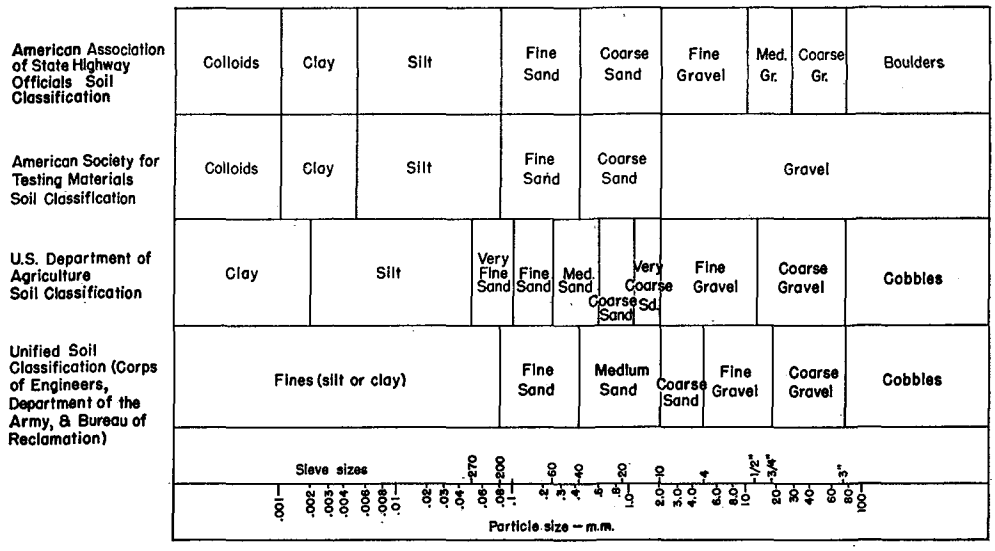


Figure 4. Different grain size boundaries define the soil factions in the various classification schemes.

Moisture Content

The moisture content of a soil is the ratio, expressed in percentage, of the weight of water in

a quantity of soil divided by the dry weight of that soil. In fields other than engineering the moisture content may express the weight of the water as a percent of the original wet weight of the soil (dry soil plus water); however, the engineering definition is usually used in earth house construction.

Atterberg Limits

Tests have been devised and standardized to determine the moisture content of a soil when it changes from one state of consistency to another. The four states usually considered are solid, semi-solid, plastic, and liquid; boundary moisture contents between these four states are shrinkage limit, plastic limit, and liquid limit, respectively. These limits are called Atterberg Limits after the Swedish soil scientist who devised them.

The **shrinkage limit** is the moisture content at which shrinkage of the soil will cease with further moisture loss. This condition is an important consideration in earth construction as shrinkage cracks are usually detrimental to a building. Since clay is the major soil fraction that causes shrinkage, the shrinkage limit of a soil is a general index of clay content.

The **plastic limit** of a soil is the moisture content at which a soil changes from a semi-solid to a plastic state. This condition is said to exist when the soil begins to break or crumble when rolled into 1/8-inch diameter threads. The plastic limit is governed to a high degree by clay content. Some silt and sand soils that cannot be rolled into 1/8-inch threads at any moisture content have no plastic limit and are termed nonplastic.

The **liquid limit** is the moisture content at which a soil changes from the plastic to the liquid state. It has been defined as the moisture content at which the sides of a 2-mm-wide groove cut in the soil flow together a distance of 0.5 inch under the impact of 25 blows in a standard testing device. Sandy soils have low liquid limits of the order of 20, whereas silty clays and clays have significant liquid limits that may be as high as 80-100.

The **plasticity index** is defined as the numerical difference between the liquid limit and the plastic limit. It has been correlated to the engineering behavior of soils, and it is an excellent indicator of soil performance. Soils with low plasticity indices (less than 10-15) are volumetrically stable whereas soils with high plasticity indices (greater than 20-25) have characteristics, such as high shrinkage and swell, which render them undesirable for earth house construction.

Soil Strength

Another characteristic that must be considered is the strength of the soil. Finished brick or earth walls must have both compressive and tensile strength to sustain the loads imposed on them. The compressive strengths usually specified (around 300-350 pounds per square inch), although much less than those of concrete or timber, are adequate due to the thick wall sections used in earth construction. Tensile strength specifications are very low (50 pounds per square inch or less) since wind loads on the walls are the only principal loads producing tension.

Resistance to Weathering

Generally, four types of weathering processes must be considered in earth construction. They are:

A. Wetting and drying.
B. Freezing and thawing.
C. Erosion by rain.
D. Abrasion.

Tests have been devised to measure the resistance to these weathering processes.

Although it would appear that the sand-clay ratio of a soil should influence its weathering properties, authorities do not agree on the correct ratios. At Clemson College[40] investigators found that mixtures increased in weather resistance with higher percentages of clay. However, at South Dakota,[84] the reverse was reported. It is possible that different types of clay minerals in the soils caused this apparent contradiction, since these two soils fall in different great soils groups.

Absorption

Absorption of water into an earth building material may be caused by both permeability and capillarity. As the proportion of sand increases, the pore spaces become larger, resulting in increased permeability; however, too many fines will allow water to penetrate the soil by capillarity. In general, the best sand-clay ratio to prevent water passage must be determined by absorption tests for the specific soil in use.

Soluble Salt Content

Some soils containing large amounts of soluble salts are unsuitable for earth wall construction. In addition to having a high affinity for water, these soils are difficult to stabilize with certain chemical stabilizers. Such soils are peculiar to arid and semi-arid regions. If their presence is suspected, the builder should send samples of the soil to a soils laboratory for analysis.

Soils for Rammed Earth

Gradation

Most authorities have agreed that a narrow range of grading must be used to obtain satisfactory results with the rammed earth method. A range of 60 to 75 percent sand (coarse fraction) is usually specified. There are two reasons for this close control. The first concerns shrinkage cracks. A monolithic earth wall is very susceptible to damage by shrinkage cracks, whereas in block construction the shrinkage occurs during the curing period before the block is placed in the wall. Since high clay content soils usually have high shrinkage, they are undesirable for rammed earth.

The second reason for the close control on the grading is its relationship to the strength of the soil. Trials can determine a grading that not only will meet the other criteria but also will result in a high strength. This selected grading must then be con-

trolled throughout the construction if consistent results are to be obtained.

Years ago, rules of thumb were used to select soils for rammed earth construction. Although modern methods of soil analysis give more accurate indications, the older methods are still practical for selecting a few soils for analysis from a large area. Merrill[74] quotes an older source as such:

> "Strong earths (are fit for this purpose) with a mixture of small gravel, which are refused by brick makers and potters. These gravelly earths are very useful; the best pise' (rammed earth) is made from them; but from experience in building . . . what is to be understood as gravel had better be explained. Gravel, fit to be amongst building earths, should consist of small round pebbly stones; not flat, shelly, or slaty ones. The round stone in ramming packs equally well on all sides, but a flat stone will resist the stroke . . . and never lie solid and firm.
>
> "The following appearances indicate that the earth in which they are found is fit for building: when a pickaxe, spade, or plow brings up large lumps of earth at a time; when arable land lies in clods or large lumps, and binds after a heavy shower and hot sun; when field mice have made themselves subterraneous passages in the earth, and these are clear and smooth . . . all such are favorable signs.
>
> "When the roads having been worn away by the water . . ., are lower than the other lands, and the sides of these roads support themselves almost upright, it is a sure mark that pise' may be practiced there . . . It (suitable soil) is also found at the bottoms of the slopes of high lands that are cultivated because every year the rain brings down the finest particles. It is frequently found on the banks of rivers. In digging trenches for buildings or cellars, it frequently happens that what comes out of them is fit for the purpose: or may easily be made so by an admixture of other soils with them."

Atterberg Limits

Since the Atterberg limits can predict the shrinkage and the approximate strength potential of a soil, they are excellent guides to soil selection. According to Koch,[57] for a good rammed earth mix the liquid limit should be less than 35, the plasticity index between 2 and 15, and the shrinkage limit less than 25. Koch also states that the shrinkage limit of the selected soil should be greater than the optimum moisture content. (See Page 17 for explanation of optimum moisture content.) Application of the latter criterion will eliminate shrinkage cracks in the wall.

For lateritic clays, which shrink and expand less than temperate zone clays, the Atterberg limit values given above may be too low. However, quantitative correlation is not available to establish new criteria for laterites.

Strengths

If proper compaction is obtained to produce a density of around 130 pounds per cubic foot of the in-place moist soil, the required strength of 300-350 pounds per square inch will usually be exceeded.[82] In addition, early investigations[88] showed that the strength of rammed earth walls increased with age; as much as 45 percent strength increase after three years was reported.

Other Considerations

The desirable sand-clay ratios are determined by the considerations discussed above, and the best ratio for weathering resistance may not always be used. When this occurs, stabilizers and/or protective coverings will be needed to furnish the durability.

The same situation is true with regard to soil selection for protection against absorption. The normal mixes used in rammed earth are coarse enough to limit capillary rise effectively. On the other hand, the permeability may be high enough to allow water that comes in contact with the surface to penetrate the wall. Again, stabilizers and protective coverings will be needed in most cases to waterproof the walls.

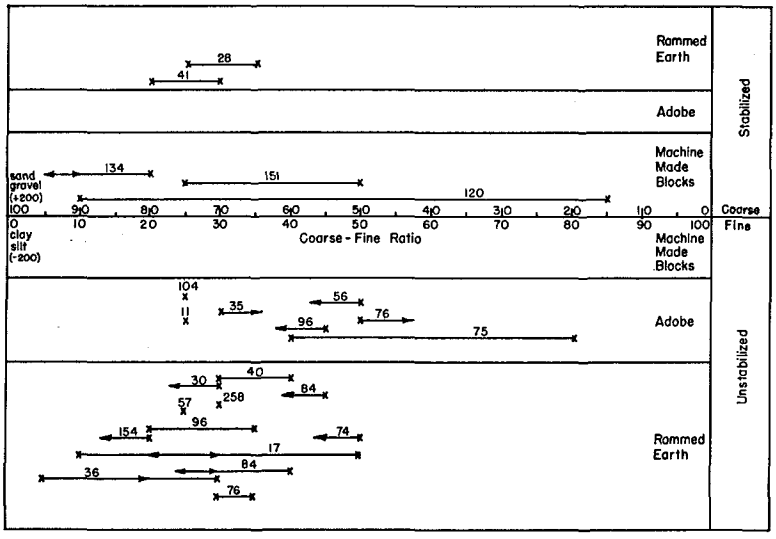


Figure 5. Compilation of grading recommendations for various types of earth home construction.

Soils for Adobe Blocks

Gradation

The grading limits for successful sun-dried adobe blocks are considerably more lenient than for rammed earth. Kirkham states that almost any earth can be used for making blocks provided it contains at least 50 percent sand.[56] The clay content should be high enough that the block will have a high cohesive strength when dry. In general, it may be assumed that a good agricultural soil containing loam, silt, and organic matter is not suitable for adobe while a soil higher in clay and sand content, but poor in regard to crop production, is usually more satisfactory. One author[59] states that any soil within the limits of 80 percent clay—20 percent sand will make satisfactory adobe blocks. A compilation of grading recommendations taken from 22 references is

Figure 6. Close-up view of Ft. Davis, Texas, adobe wall demonstrates large aggregate in the adobe blocks.

shown in Figure 5. Three methods of earth wall construction are considered.

In Figures 6 and 7, extreme examples of grading are illustrated. The Ft. Davis, Texas, adobe contained considerable coarse material including large gravel sizes. The strength and absorption characteristics were favorable. On the other hand, the high clay content (82 percent fines) of the Ysleta, Texas, adobe provided an unsatisfactory surface and poor engineering qualities.

Atterberg Limits

To date, the meager scientific evaluation of soils for adobe has produced inconclusive criteria with regards to the Atterberg limits. Therefore, no standards are recommended.

Other Considerations

Test results on preliminary mixes will influence the selection of soils with respect to the remaining soil characteristics. Enough soils should be selected for trial so that a reasonably successful mix will be included.

The use of straw or other fibers in adobe is a controversial subject. In India[81] jute fiber was reported to have contributed additional weathering resistance. Neubauer[96] reports that the advantages of adding straw to the mix are doubtful. He suggests that its use might improve drainage and ventilation through the block (during curing), promote uniformity of drying, assist in avoiding checks and cracks, and perhaps improve the tensile strength of the blocks. Neubauer indicated that many present-day successful manufacturers are not using straw. Harrington[42] discounts the use of straw and considers that it reduces the compressive strength of the block. It is interesting to note that samples of adobe taken from the 100-year-old community building at Ysleta, Texas, Figure 8, contained straw free from rot or deterioration.

Soils for Machine-Made Blocks

The manufacturer of one block-making machine claims that any soil containing the correct proportions of sand (not defined) and not less than 18 percent clay is suitable for use if stabilized. Undoubtedly, lateritic soils and many other soils throughout the world may be used effectively without stabilizing admixtures. It is probable that soils suitable for rammed earth will show reasonably similar properties when pressure-compacted in machines. Soils for machine-made blocks cannot contain the large gravel sizes that are satisfactory in rammed earth mixes, and it is necessary to remove gravel larger than ½ to ¾ inches. As in rammed earth, the optimum moisture content for each soil and machine compactive effort must be determined by trial.

A soil used successfully in India at the Central Road Research Institute[21] in a Landcrete machine had the following physical constants:

Liquid limit	31.4
Plasticity index	13.8
Sand content	35.0%
Clay (and silt)	65.0%

This soil produced a compressive strength of 813 pounds per square inch when compacted at the optimum moisture content.

Since the objective of the machine is to produce high strength uniform blocks, consideration must be

Figure 7. The clay content in the adobe blocks in this ruin at Ysleta, Texas, was excessively high, resulting in severe checking of the surface.

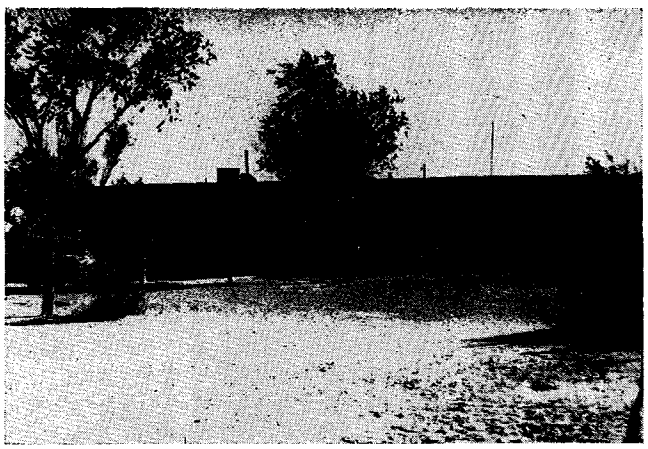


Figure 8. Straw from adobe blocks in this 100-year-old community building at Ysleta, Texas, showed no signs of rot or deterioration.

given to prevent shrinkage. According to findings of researchers with rammed earth, cracking can be prevented by selecting a soil whose shrinkage limit is equal to or above the optimum moisture content. This will require a selective gradation.

Soils for Other Construction Methods

Cob and wattle and daub construction require the least consideration for soil selection. In wattle and daub, shrinkage cracks do not adversely affect the strength of the wall since the brushwood framework is the skeleton for the wall. Cracks may be patched with mud plaster as they appear. The primary requirement is that the soil have enough cohesion (clay content) to adhere to the frame.

In the cob method, shrinkage cracks will affect the strength of the wall. However, since the wall is made up of small balls or lumps of material, the cracks are very small and evenly spread over the entire wall. This has a good effect in providing a bond for surface coatings. Normally, the cracks in cob work do not concentrate to form a single damaging crack.

The absorption and weathering characteristics of the soils for these two methods have seldom been investigated by builders. However, their consideration is important in maintaining dry, durable walls.

SOIL STABILIZATION AND SURFACE COATINGS

General

Probably the outstanding weakness of earth walls is their susceptibility to damage by moisture; therefore, a wall which is not protected against excessive water absorption will not last for a long period of time. Moisture may be absorbed by splashing, by dripping from projections, from a leaking roof, or by capillarity from the ground through the foundation. Rains directly against earth walls are not always damaging unless the interval between rains is too short to permit drying. This is particularly true in freezing weather.

Rainwater can be very damaging if it is channelized on the earth wall surface. Rivulets from the roof, rain gutters, window sills or other projections can erode an unstabilized wall with ease. Figure 9 is an excellent illustration of this situation on an unstabilized wall in Albuquerque, New Mexico.

Protection—usually by a resistant surface coating —is also needed against the abrasive effects of wind-driven sands.

The damage by these weathering agents often limits the effectiveness of plain earth construction. When relatively maintenance-free buildings are desired, stabilizers, surface coatings, or both, should be incorporated in the construction.

Soil Stabilization

Methods of Soil Stabilization

Soils are stabilized for the purpose of improving one or more of their basic properties. This is usually done by one of the five methods given below:[26]

A. Stabilization by changes of the grain size distribution or grading.
B. Stabilization by mechanical means.
C. Stabilization with chemicals.
D. Stabilization by combined means.
E. Stabilization by electro-chemical action.

Stabilization by method A is achieved by adding to the original soil certain materials such as sand, fine gravel, broken stone, or such fibrous substances as sawdust, wood shavings, and similar materials. If sand or gravel is added, the grain size distribution of soil is changed to the extent that products made from the soil will shrink less. As a rule, no increase in compressive strength of soil products is achieved by the addition of fibrous materials, but it has been claimed that their resistance to tension increases and therefore they will crack less during the process of drying.

Mechanical stabilization is based on the principle of improving the adhesion between the soil particles with the aid of a stabilizer. This may be achieved, for example, by mixing a bituminous emulsion with the soil. The emulsion coats the soil particles in thin films resulting in increased adhesion between the particles as the volatile substances present in the emulsion evaporate. In the fine grained soils, which already possess cohesion, the bitumen waterproofs the soil grains so that the cohesive strength can be retained.

Chemical stabilization is based on the chemical interaction of the soil and the stabilizing agent, of which lime, calcium-chloride, and substances obtained during the process of decay are examples. Many different chemical stabilizing compounds are on the market. They are more or less available throughout the world; and although some of them (for instance, aniline furfural) do an excellent job, they do not always compete economically with other stabilizers. Some of the lesser known chemicals such as sulfite liquor are locally available throughout the world as industrial waste products. Such materials are useful

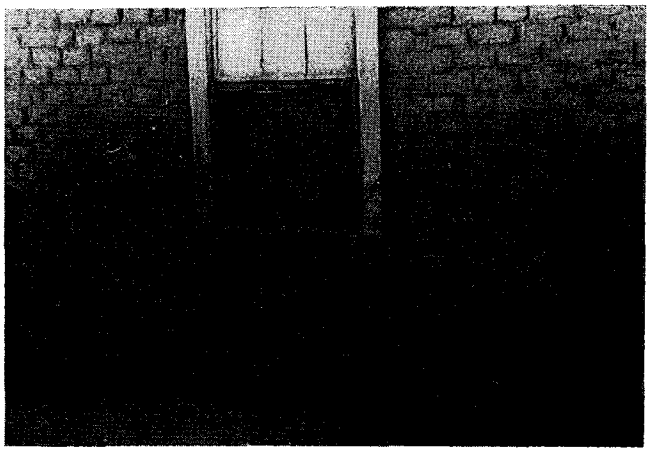


Figure 9. An overhanging window sill channelizes the rain into two rivulets, easily eroding the unprotected, nonstabilized wall surface.

stabilizers and in some areas may replace some of the more common materials.

Combined stabilization is exemplified by such admixtures as portland cement, lime, gypsum, and others which act upon the soil both by mechanical and by chemical means.

Electro-chemical stabilization is achieved through the action of a direct electric current upon a soil containing carbonates, gypsum, metal salts, etc. The use of this process in earth house construction has not been reported in the literature.

Portland Cement

It may be generally stated that the quantity of portland cement required for stabilization of a soil depends upon the type of the soil and the method of preparing the soil-cement mixtures. Less cement is required to stabilize a soil composed mainly of sand, particularly when the sand is properly graded. Cement demand increases as the silt and/or clay content increases. Other factors being equal, a higher quantity of cement is required for stabilization of a wet soil mix than for a moist soil mix.[26] Practically speaking, however, it is more difficult to obtain thorough mixing with moist mixes than with wet mixes. Since the effectiveness of a stabilizer is a direct function of the efficiency of mixing, it might be argued that wet mixes are more practical. Nevertheless, it is usually more desirable with cement stabilization to use a sandy, moist soil taking proper precautions to obtain thorough mixing.

Soil stabilization with cement is not new. Considerable research has been devoted to studying its use in the construction of roads and airfields. However, only a few research projects have involved the direct application of cement stabilization to earth wall construction. Much of the accepted practice today is based on successful experience with particular combinations on the job. To illustrate current practices in the use of soil-cement, several of the more comprehensive references are reviewed below.

Ref. 134 (South Africa)—This report contains the results of investigations of various compacted soil and soil-cement mixtures for use in buildings. In particular, the discussion concerns the effects of soil characteristics, molding moisture contents and cement contents on the density, durability, water permeability and compressive strength of soil-cement units made from various soils under different conditions.

Some of the conclusions based on this research are listed below:

A. The density of the blocks decreases as the clay content of the soil increases.
B. The dry compressive strength and the ratio of wet to dry compressive strength increases with increased cement content. The strength of blocks molded from sandy soils is generally slightly higher when the total moisture content in the mix is below the optimum. With clayey soils, the opposite is true.
C. Stabilization of sandy soils is more effective than that of clayey soils. Blocks molded from sandy soils are generally stronger and shrink less during drying.
D. Blocks molded from sandy soils lose moisture much quicker than those molded from clayey soils.
E. Permeability of the blocks decreases as the cement content increases.
F. Unstabilized specimens failed to survive one cycle of a wet-dry weathering test. Six-percent cement blocks lost nine percent weight after 20 cycles. Twelve-percent cement blocks lost one percent weight after 20 cycles.
G. For the production of soil-cement blocks, soils with a maximum grain size of 10 mm are recommended. The material finer than 0.005 mm should not exceed 20 percent by weight and should preferably be below 10 percent. The plasticity index should not exceed 20 and should preferably be below 10, while the linear shrinkage should not exceed 6 percent and should preferably be below 4 percent.
H. Cement contents less than 6 percent by weight are not recommended.
I. Blocks should be cured for at least two weeks and should be kept damp and protected from direct rays of the sun. They may be used for construction of walls about four weeks after manufacture when well air-dried.
J. It is recommended that after 28 days of curing followed by 24 hours of immersion, the compressive strength of the blocks exceed 15 kg/cm^2 (about 210 psi) and the moisture absorption be less than 12 percent.

Ref. 26 (Israel)—An earth house construction program was initiated in Israel in 1953. The research supporting this project contributed a number of worthwhile facts about stabilized soil construction. Some of the conclusions follow:

A. A fine, sandy clay (51 percent sand and 49 percent clay) failed in all respects due to insufficient moisture in the mix during molding and to unsatisfactory curing.
B. Six-percent cement provided adequate compressive strength for a well-graded, sandy clay (54/46 ratio). Cement contents in excess of six percent for this soil increased the compressive strength but improved the resistance to water absorption very little.
C. A sand with little fines (94/6 ratio) possessed adequate strength but failed in absorption.
D. The addition of 6, 8, and 10 percent cement failed to improve the performance of two of the soils (76/24 and 77/23 ratios).
E. It was desirable to utilize a waterproofing agent along with the cement. After using such an agent, all of the soils passed the absorption and compressive strength tests with six percent cement.

University of California (by letter August 18, 1959—This research used the CINVA-Ram machine to make blocks from local soils.

A. High compression with the machine increased the strength of the soil-cement block by at least 50 percent.
B. Machine-made blocks of soil-cement were less absorbent than wet-mix poured blocks (adobe) of the same cement content.

C. As the cement content increased, water absorption decreased.
D. Addition of small quantities of cement up to six percent lowered the strength of the blocks. The addition of eight percent cement did not increase the strength of the machine-made blocks over plain adobe (dry strength), yet it had a very marked advantage in increasing water resistance.
E. The addition of as little as two percent cement gave a definite increase in water resistance.

Ref. 111 (Portland Cement Association)—The following comments relative to experimental soil-cement building construction with wet and moist soil-cement mixtures are based upon the results of research tests, upon observations of soil-cement buildings, and upon 1946 construction practices for raw-earth methods of construction, i.e., adobe and rammed earth construction.

A. At present, soils used to make soil-cement blocks or construct cast-in-place walls should be limited to U. S. Public Roads Administration soil groups A-2-4 and A-4 which contain less than 50 percent fines (silt and clay) having usual affinity for cement and which may be hardened with relatively low percentages of cement.
B. Wet soil-cement mixes will require about four percent more cement than moist mixtures of the same soil.
C. Adequate cement contents for moist soil-cement mixtures will vary from about 6 to 12 percent by **volume** of the compacted specimens and from about 10 to 16 percent by volume of the puddled specimens for wet soil-cement mixtures.

Ref. 21 (Central Road Research Institute, India)—The following results are based on a preliminary investigation using soil-cement blocks made by the Landcrete machine. A local soil was used that is well suited for block manufacture.

A. For a clayey soil (35 percent sand and 65 percent clay, liquid limit of 31.4, plasticity index of 13.8) the following strengths were reported:

Cement Content %	Compressive Strength, p.s.i.		72-Hour Soak
	Oven Dried	Saturated	
2.5	1545	226	15
5.0	2055	552	14

The very low strengths after the 72-hour soak period again indicate that a water-proofing admixture may be necessary in addition to the cement for construction in wet areas.

Ref. 120 (Bogota, Colombia)—At Bogota, Colombia, during 1949 and 1950 an engineering study was carried out for the Colombian government to evaluate the factors involved in using soil-cement for simple structures. It was found that small quantities of cement—as low as two to eight percent by weight—stabilized most of the hundreds of soil types tested except those containing greater than 85 percent or less than 10 percent clay, or with more than 8 percent organic matter.

Ref. 73 (India)—In this research it was found that the shrinkage of soil compacted at the optimum moisture content decreased as the cement content increased. Even with 20 percent cement, some shrinkage still existed. The four soils presented in Table 1 were tested.

TABLE 1

No.	Description	Liquid Limit	Plasticity Index	Sand Content
1	Sandy Loam	21.8	4.9	65.0
2	Silty Loam	27.5	8.7	18.8
3	Silty Clay Loam	37.0	17.3	8.4
4	Loam	25.7	9.5	43.4

The percentage of shrinkage based on the shrinkage of the untreated soil for various cement ratios is shown in Table 2.

TABLE 2

Soil	Percent Raw Soil Shrinkage	Percent of Shrinkage of Raw Soil for Cement Contents Shown				
		2.5	5.0	7.5	10.0	20.0
1	100	68	63	52	47	38
2	100	69	57	53	53	49
3	100	68	55	51	43	37
4	100	60	56	53	42	41

Based on these data, it does not appear economical to use more than 2.5 percent cement for the single purpose of reducing shrinkage.

The effect of wetting and drying was also determined on all four soils with the aforementioned cement contents. It was noticed that 2.5 percent cement was just sufficient to keep the expansion of fully saturated soil-cement blocks within safe limits. The only exception was the silty clay loam (Soil No. 2) which required 5 percent cement.

Ref. 85 (South Dakota)—This research determined the effect of admixtures on the compressive strength of rammed earth, but not upon the resistance to weathering. Fifteen percent portland cement (based on the dry weight of the soil) was added to four different soils having sand contents varying from 26 to 80 percent. For a soil which contained 26 percent sand, no added strength was provided by the cement. For the remaining soils with sand contents varying from 48 to 80 percent, the compressive strengths were doubled and almost tripled by the addition of the 15 percent portland cement.

Emulsified Asphalt

This admixture is an emulsion of asphaltic cement and water containing a small amount of emulsifying agent (usually soap). There are many types and grades of asphaltic emulsions and care must be exercised in selecting the proper one for the particular job. Emulsions "break" or settle out at varying rates of time and come as fast-, medium-, or slow-breaking emulsions. Slow-breaking emulsions are best suited for earth construction.

The primary function of an asphaltic emulsion is not to increase the compressive strength but to retain the original dry strength of the raw soil through waterproofing. In fact, the strength of the stabilized mix will often decrease with increasing asphalt content. Therefore, the minimum amount of asphalt that will satisfactorily waterproof the mix is the optimum content.

The amount of emulsion to be added to a particular soil mix is best determined by trials. To narrow the scope of the trials, a good rule of thumb is that the more nearly correct emulsion contents will fall in the range of 20 to 30 percent by weight of the combined silt and clay fractions of the soil.[41] Within this range, values can be selected for trials to determine the optimum content.

Several research agencies and builders have reported their experiences with this stabilizer. In the United States the primary commercial organization that fosters this type construction is the American Bitumuls and Alphalt Company, San Francisco, California. Their product, Bitudobe, is an emulsified asphalt suitable for stabilizing soil blocks. No mention is made in their literature of its application to other types of earth construction. The experiences of other agencies is summarized below.

Ref. 41 (Illinois)—The compressive strength of dry soil blocks increased with the addition of a small amount of emulsified asphalt, but it decreased after a certain amount was added. When the specimens were allowed to absorb water, the compressive strength increased as the stabilizer contents increased. An increase in stabilizer content also lowered the absorption; however, not all brands of the same specification emulsified asphalt required the same percentage. (This difference was quite likely due to differences in amount and viscosity of the residual asphalt.)

Ref. 82 (California)—Information in this publication shows that a fractional volume of asphalt emulsion provides an internal waterproofing that permanently protects adobe blocks. Such mixes may require 5 to 15 percent of emulsion to give adequate protection to various soils. Emulsified asphalt often weakens the brick in direct proportion to the amount used, but it may make the brick tougher, more elastic, and more durable. Five percent of emulsion may be sufficient to provide waterproofing.

Ref. 151 (Bitudobe)—The specified proportion per cubic foot of mud is one quarter gallon of emulsion (about three percent by weight) made from grade D asphalt of 60-70 penetration.

Ref. 26 (Israel)—The addition of two percent emulsion improved the compressive strength and absorption properties very little. Considerable improvement was obtained with six percent emulsion, but little additional improvement was obtained with ten percent.

Ref. 30 (Housing & Home Finance Agency)—The correct quantity of asphalt emulsion can usually be determined only by experiment, but it appears to depend primarily upon the amount of fine silt and clay contained in the soil. As a rough guide, the following table has been suggested to approximate the amount of slow-setting type emulsion which may be needed:

Sandy Loams	4 to 6%
Clay Loams	7 to 12%
Heavy Clays	13 to 20%

These rules, when used for preparing samples or making quick estimates, are helpful; but it must be remembered that the amount of stabilizer required will generally increase not only with the amount of clay in the soil, but also with the colloidal content. It should also be recognized that the water affinity of the fines in various soils may vary and that the nature of the stabilizer is variable.

Lime and Lime-admixtures

Lime as an admixture has been employed in agriculture to improve clay soils with respect to their workability, plant sustaining qualities, and transmission of surface water. It has been used by highway engineers to increase the load carrying capacity of heavy clays and reduce their softening upon saturation. In earth building construction, particularly in India, lime separately or with additives has been used to improve strength and weathering properties.

The stabilizing reaction of lime with clay soils is primarily chemical in nature. It is the result of the replacement of weaker charged metallic cations by the stronger charged calcium cations of the lime, which, in turn, influence the thickness of the adsorbed halo-like moisture films on the exterior of the clay grains. The plasticity of clay soils, which is in effect a rough measure of their stability, is considered to be a function of the thickness of the water films.[39]

In many countries, lime is an economical admixture, obtained by burning sea shells or certain limestones. In India, for instance, little, if any, experience is reported with asphalt while an abundance of reports on lime stabilized soils exists. Quite often lime is mixed with a pozzolanic material. An example is surki, which is locally manufactured in India by pulverizing burnt bricks, tiles, or pottery.

The experiences of several agencies with lime are listed below.

Ref. 101 (Indonesia)—Experiments were performed in 1952 with hydrated lime and a pozzolan. The soil type was unidentified. Pozzolan was used in the ratio by volume of 5:1 with the hydrated lime. The greatest strength occurred at a certain optimum admixture. Admixture contents both higher and lower than the optimum content produced lower strengths.

Ref. 26 (Israel)—Blocks were prepared with the Landcrete machine from the five types of local soil previously described. The soils were treated with 6, 8 and 10 percent lime by weight and tested at the age of 28 days. Although these blocks did not pass the criteria of this investigation, they were considerably more moisture resistant than unstabilized blocks. As mixes containing lime harden more slowly than those containing cement, better results might have been obtained with a longer curing period.

Ref. 110 (Iowa Engineering Experiment Station)—Although this research was directed toward highway use, it appears appropriate for earth house construction. Four silty and clayey soils were stabilized with lime-flyash. Shrinkage limits for the untreated soils were considerably lower than the optimum moisture

contents; the sand-clay ratios for the four soils were 8:92, 3:97, 1:99, and 8:92. Obviously, these soils would not have been suitable for earth construction without stabilization.

The conclusions of the study were as follows:

A. Lime-flyash decreased the maximum dry density and increased the optimum moisture content.
B. Lime-flyash materially improved the compressive strengths of soaked samples. Untreated samples failed during immersion while stabilized samples gave 64 to 223 psi compressive strengths after 7 days' moist cure and 360 psi after 28 days' moist cure.
C. With 25 percent lime-flyash, strengths varied slightly for lime to flyash ratios from 1:1 to 1:9.
D. For a given lime to flyash ratio, compressive strengths increased with increasing percentages of admixture.

Ref. 96 (West Africa)—Lime has been used successfully with a pozzolan made by burning bauxite.

Other Chemical Stabilizers

A large number of chemicals have been tested and found to be of some benefit in either waterproofing or cementing soils. The individual performance records of each chemical will not be enumerated; however, the source of the information is listed with the chemical.

Ref. 113 (Massachusetts Institute of Technology)

(1) Polyvinyl alcohol (Dupont) ½ to 1½ percent, used to improve soil-cement.
(2) Daxad 21 (Dewey and Army) 1 percent, used with soil-cement.
(3) Sodium tetraphosphate (Rumford Chemical Co.) 1 percent, used with soil-cement.
(4) Tamol 731 (Rohm and Haas) 1 percent, used with soil-cement.
(5) Calcium acrylate, 0.1 to 0.5 percent, used with soil-cement.
(6) Calcium polyacrylate, 0.1 to 1.0 percent, used with soil-cement.
(7) Resins, polyacrylamide, 0.5 percent, used with soil-cement.

Ref. 110 (Highway Research Board)

(1) Resin 321 (also Ref. 17) 0.2 to 0.5 percent.
(2) Vinsol (also Ref. 17) 1 to 2 percent.
(3) Aniline-furfural resin, 2 percent.
(4) Tung oil.

Ref. 26 (Israel)

Several chemicals were tested that increased the water proofing characteristics but adversely affected the compressive strength.

The chemicals were:

(1) Silicate of soda (locally produced).
(2) Frigor (locally produced).*
(3) Fluorite (locally produced).

*Frigor is a liquid produced from Dead Sea water, possessing a unit weight of 1.38 g/cm³ and containing 394 g/liter of magnesium chloride, 109 g/liter calcium chloride, and a total quantity of 8 g/liter of potassium and sodium chloride.

Ref. 83 (Sulphite Liquor)

Sulphite liquor imparts cohesive strength to a soil as well as making it relatively impervious to water. A process was developed by Smith and Hough in 1951 using sulphite liquor combined with potassium or sodium bichromate.

Other Stabilizers

With the exception of portland cement and lime, most stabilizers used in foreign countries have been locally available products. Based on its obscurity in the foreign literature, emulsified asphalt has evidently not been readily available. Most chemical stabilizers have either been too expensive or overlooked. As a result, the builder of low cost homes has turned to locally available and inexpensive materials that appear to benefit the construction.

Organic admixtures have been in common use. Manures, fibers, and rotted plants have been traditionally used although normally discredited in American engineering papers. Most of the organic processes involved are reported in agricultural rather than engineering publications. Since these materials are in such general use, a comprehensive engineering study of their application is warranted; such studies are not presently available.

The materials included in the following list have been reported by various sources as being beneficial to soil stabilization:

A. Cow dung.
B. Grass.
C. Flax straw.
D. Oat straw.
E. Tannic acid.
F. Jute fiber.
G. Surki (a pozzolan made in India).
H. Cattle urine.
I. Rotted plantain leaves (West Africa).
J. Molasses.
K. Sawdust and wood shavings.
L. Juice from **Euphorbia lactia** plants or **Optintia** plants (principally in Venezuela and Union of South Africa, but common to nearly all tropical countries).
M. Gum arabic.
N. Hardwood ashes.

Surface Coatings

In an effort to prolong the life of earth structures, surface coatings have been applied to limit erosion and water absorption. In some moderate climates, surface coatings are needed only on unstabilized earth construction. In severe climates both surface and internal forms of protection are needed. Sometimes, surface coatings are applied only to improve the appearance of the wall, especially interior walls.

As in the case of internal stabilizers, the use of portland cement has been generally satisfactory for coatings, but in most areas cheaper substitutes are necessary. Various mud plasters, dung washes, lime stuccoes, and plant juices have been used.

In the development of wall treatments, the requirements discussed below have been established.

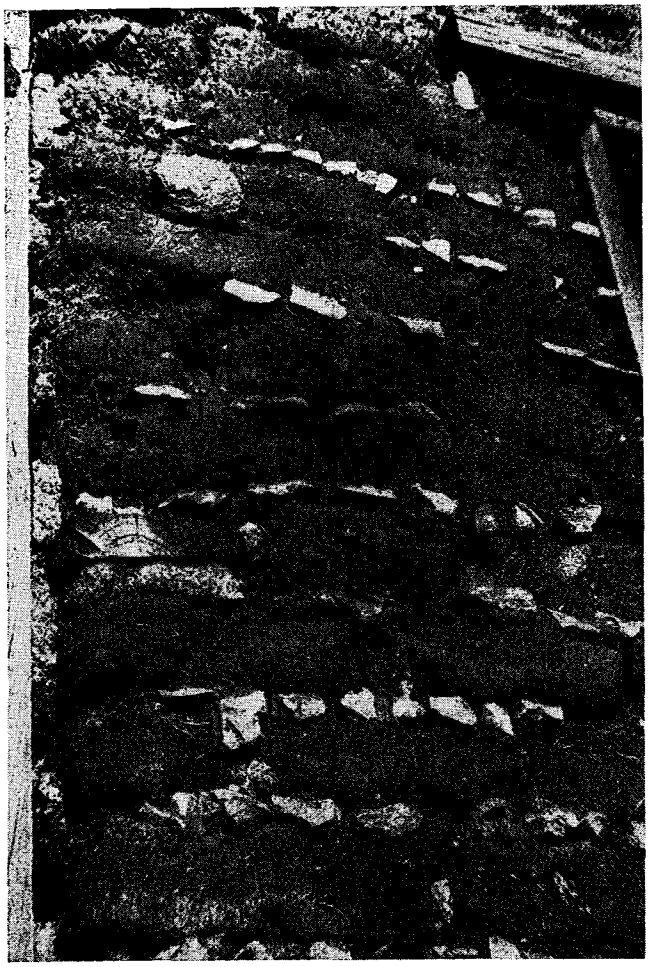


Figure 10. The mechanical bond of plaster to the adobe wall was enhanced by the early builders of Ft. Davis, Texas, by inserting rock chips in the fresh mortar.

Watertightness

Since the purpose of a protective covering is to prevent water from entering the earth wall, any covering that is permeable enough to pass water is unsatisfactory. In this respect, some mud plasters and cement or lime stuccoes perform unsatisfactorily due to a high sand content. The proper sand content must be carefully determined since too little sand will result in checking of the covering and too much sand produces a permeable surface.

Durability

Most wall treatments are made of better material than the wall itself. High cement contents give a strength that is sufficient to resist weathering. The principal structural weakness in the wall treatment is that of bond to the underlying earth. Normally, mechanical bonds such as lath or wire will prevent failure, but they add significantly to the cost. Cheaper but less effective mechanical bonds can be made by placing nails in indentations. At Ft. Davis, Texas, built in the 1860's, rock chips were embedded in the fresh mortar joints to provide a good bond (Figure 10). Cement washes (portland cement and water) have also been used as an undercoat to improve the bond. Unless a special bonding agent is used, satisfactory results can usually be obtained only on high sand content walls.

Appearance

Most home builders will want new homes to have a pleasing appearance. Checked or cracked plasters present a very poor appearance, as well as failing to protect the wall. Generally, asphalt or tar admixtures in the coating result in a color too dark to suit most people. The most attractive color is usually obtained from cement or lime stuccoes. The resulting light color also provides a more cheerful and better lighted interior because of higher reflection.

Economy

The prevalence of mud or "dagga" plaster for surface coatings in low-income countries is reasonable proof that the more durable stuccoes are expensive. The high percentage of cement in stuccoes (usually 25 percent) accounts for the high cost.

The solution for improved coatings in areas where cement or lime is not economically available will be in the improvement of the dagga plaster. Grading, consistency, technique of application, and materials can be improved. For example, West Africans have discovered that a kaolin-rich clay can be used as an admixture to the regular dagga plaster to give good results. This most likely is accounted for by low shrinkage and reasonably high dry strength peculiar to kaolinitic clays.

TESTS

General

Adequate testing is a necessity for successful earth construction. Performance of soils depends on so many variables that theoretical methods of design are often impractical. Generally, it will be necessary to prove the final design by strength and weathering tests on full scale building units (either blocks or small sections of a wall).

Soil testing for earth houses can be divided into three parts:

A. Expedient soil tests that can be performed with a minimum of equipment by persons who are not qualified soil technicians.
B. Standard soil tests that apply to earth residential construction and which require the services of a soils technician and an equipped laboratory.
C. Special soil tests designed especially for earth residential construction that require the services of a soils technician and an equipped laboratory.

For projects involving the construction of several units, it may be economical to construct field laboratories to perform some of the tests in categories "B" and "C."

Soil Properties Requiring Evaluation

Before the testing methods are discussed, it is appropriate to list and explain the soil properties that should be evaluated in a comprehensive testing program.

Compressive Strength

The unit compressive strength is commonly expressed in pounds per square inch (psi) for the smallest cross sectional area of the specimen normal to the crushing load. The maximum load in pounds that the specimen will withstand during the test is used for computing the unit compressive strength. For consistent results, a constant rate of deformation —usually 0.05 inches per minute—should be used.

Tensile Strength

The tensile strength is also expressed in pounds per square inch for the smallest cross sectional area of a specimen normal to the tensile force. Again, a constant rate of strain is used (0.05 inches per minute) and the maximum load recorded in the test is used for the computation.

Absorption

Absorption is the rate at which water enters a specimen due to either capillary flow or immersion. It is measured in terms of moisture gain for a specific time period. Additionally, the strength of the specimen is usually determined after the absorption period. The dry strength of even poor mixes is normally adequate to pass minimum strength requirements, but the wet strength of only the best quality mixes will pass the specifications.

Classification

It is an advantage to be able to predict the approximate performance of a soil based on a preliminary identification or classification. The Atterberg limits (discussed elsewhere in this publication) can normally provide this identification. Enough experience is available to assist the builder in making initial soil selection for construction purposes based on these limits.

Gradation

Many of the reports of past earth construction identify the soil in terms of gradation, usually by just the sand-clay ratio. Several somewhat standard tests have been devised to determine the gradation with varying degrees of accuracy.

Heat Transmission

This property is not normally determined for each construction project. Enough data have been presented in engineering papers to prove that the typical earth wall will provide better insulation than frame type construction. The insulation provided by thin (6-8 inches), machine-made block walls may be more critical since the high density of these blocks promotes faster heat transmission. A test by the National Bureau of Standards[128] showed that a machine-made block wall had more than twice the heat conductivity of a thicker adobe wall. This conductivity value is, however, still low compared to that for frame construction.

Erosion

Erosion tests have been devised to determine the loss in weight of specimens exposed to spraying, abrasion, wetting and drying, or freezing and thawing.

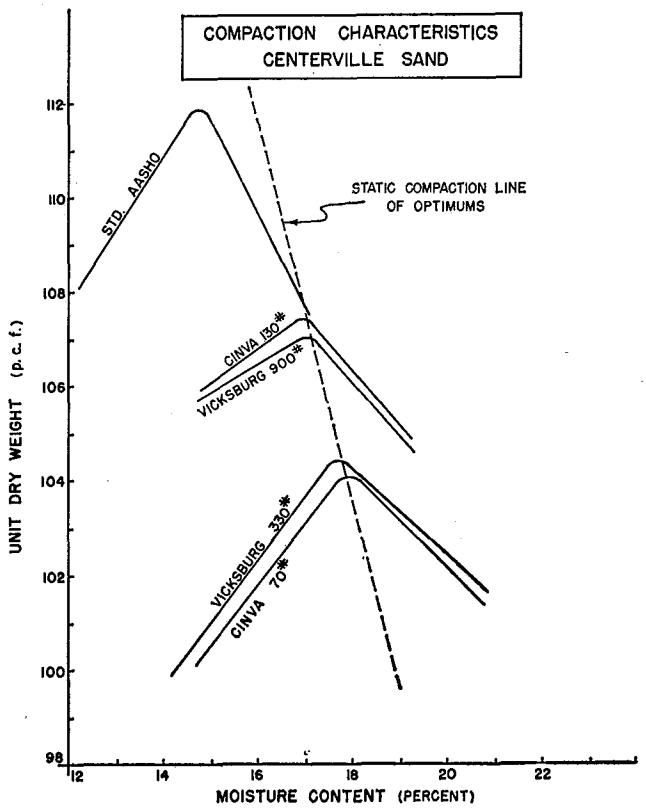


Figure 11. The moisture content-dry density chart indicates the optimum moisture content that should be used in wall and block manufacture.

Optimum Moisture Content

The optimum moisture content refers to the moisture content at which a soil attains its maximum dry unit weight for any given compactive effort. Compaction at moisture contents higher or lower than the optimum will result in low densities, low strengths, and poor volumetric stability. Since the optimum moisture content varies with the soil and the compactive effort, it must be determined by tests performed on the soil mix to be used and at the desired or anticipated compactive effort.

Typical moisture content-dry unit weight relationships at 5 different compactive efforts on a single soil are illustrated in Figure 11.

Optimum Admixture Content

Since admixtures such as cement and asphalt are expensive, it is desirable to determine the lowest quantity that can be used to meet the specifications. In the case of some admixtures, particularly asphalt, the performance suffers with too much admixture. Therefore, an optimum admixture content exists which should be determined by trial with test specimens.

Expedient Soil Tests

Below are listed several procedures for expedient soil tests taken from various references.

Optimum Moisture Content

Ram or tamp the soil mix at various moisture contents into a ½-cubic-foot box and weigh the re-

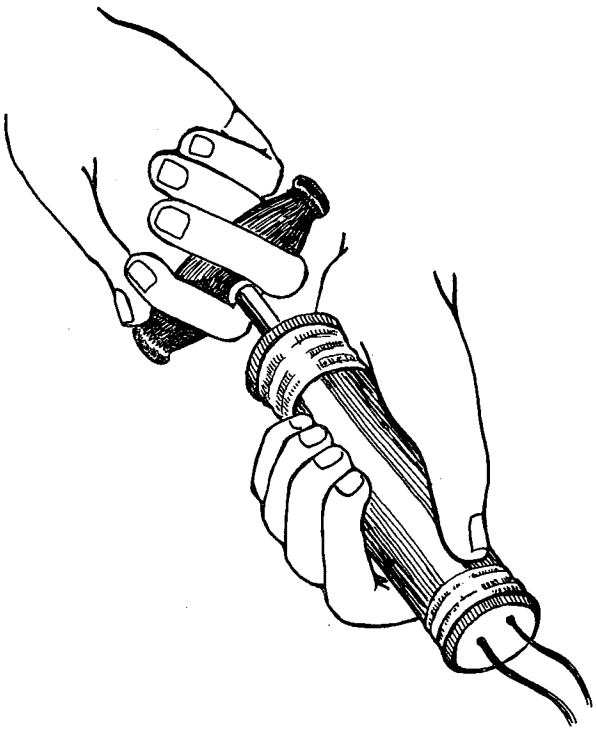


Figure 12. The Indian P. I. tube can be used as an indication of the numerical value of the P. I. for a given soil.

sultant compacted mass at each separate moisture content. The compactive effort, i.e., the number of tamps per layer and the number of layers, should remain the same for each moisture content. The moisture content at which the compacted mass has the greatest weight is the approximate optimum moisture content for the compactive effort used.

Greater accuracy can be obtained by determining the dry unit weight and plotting a curve of dry unit weight against moisture content as illustrated previously in Figure 11.

Classification

Visual classification is possible after the builder has gained some experience. In addition, there are several expedient methods for determining the plasticity index of soils that require a minimum of specialized equipment. One such method developed in India[71] utilizes a tube about six inches long and one inch in diameter (Figure 12). A cap with two or three holes of 1/8-inch diameter is placed on one end of the tube. A sample of moist soil is then placed in the tube and compressed with a plunger. The condition of the soil extruded through the holes is proportional to the plasticity index. Soils with a plasticity index less than seven usually do not form continuous threads. For a plasticity index of seven to eleven, threads are formed but the filaments have a hard, polished surface. The soil flows smoothly out of the holes if the plasticity index exceeds about eleven.

Gradation

Place three to four pounds of the sample in a flat pan and dry it in an oven or over a flame. Next pulverize the soil to break up the lumps of fine material. Fill a quart jar about one-half to three-quarters full with the dry soil, tamping the soil so it will pack tightly. Mark the level of the soil on the side of the jar and then fill the jar with water. (It is important that the jar be free of grease.) Shake the jar well and slowly pour off the dirty water, being careful not to allow sand to flow out. Repeat this operation until the wash water is clear, and the remaining residue will then be sand and gravel. Dry the residue, tamp well to settle, and estimate the percentage of the original mix remaining.

At best, this method is a rough approximation, although greater accuracy can be obtained if a weighing scale is available. In this case, instead of determining the volumes, merely weigh the material before and after washing and drying. The loss of weight, expressed as a percentage of the original dry weight, is the amount of fines in the mix.

Resistance to Weathering and Determination of Optimum Admixture Content

Based on visual classification or other preliminary tests, select those soils considered to be the best for the desired construction method. Varying the admixture content, make several test specimens with each soil. After curing, subject the samples to alternate immersion in water at night and exposure to sun in the day and observe the results. Discard mixtures which rapidly disintegrate, crack excessively, swell, burst, flake, or show any other defects. If more than one mixture passes the test, base the decision on compressive strengths and relative economy.

Correct Moisture Content for Adobe Blocks

Mix the soil, water, and admixture (if used) until a well-dispersed mix is obtained. With a V-shaped stick, cut a groove in the mix. If the sides of the groove are not smooth, then more water should be added. If the sides of the groove are smooth and bulge out, then the mix is proper. The mix is too wet if the groove closes.

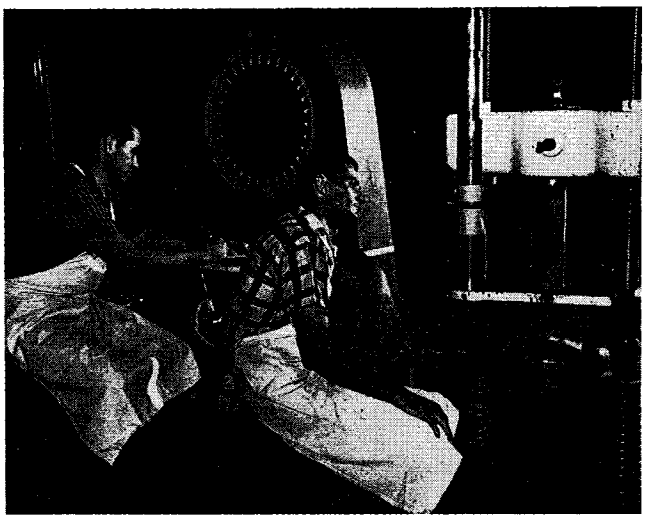


Figure 13. In the laboratory a universal testing machine can be used to determine the unconfined compressive strength of a sample. The sample being tested is a CINVA-Ram block.

Figure 14. Basic soil constants and relationships for soil samples are obtained in the laboratory with standardized testing equipment.

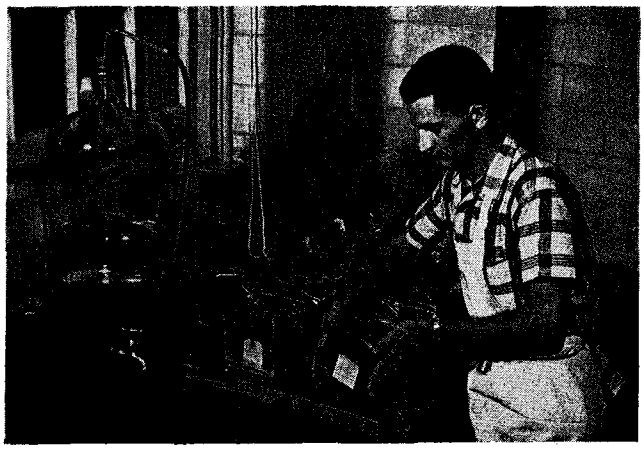


Figure 15. Laboratory facilities provide close control of special soil tests such as the absorption test above. This test may be performed in the field with minor modifications.

Correct Moisture Content for Rammed Earth and Machine-Made Blocks

If the mix is at the correct moisture content for tamping or compacting, a cast of the mix formed by pressure in the hands can be broken apart with some effort. If the mix is too dry, the cast will crumble easily; and if too wet, the cast will deform without crumbling and will have low strength.

Standard Soil Tests

The tests listed below are standard tests normally used in all types of earth construction. Because detailed procedures are available in the references indicated, only a brief description will be given below.

Compression Test

Compressive strengths are usually determined on full scale blocks or on smaller (2- to 4-inch diameter) specimens made under the same conditions as the blocks. The smaller specimens may be tested with precision testing equipment and are often advantageous since less material is required. Full-scale blocks may be necessary in special studies or when the testing equipment is not sensitive to light loads. Figure 13 shows a full-scale machine-made block being tested in a laboratory-installed hydraulic testing machine.

Standard testing machines can usually be adjusted for the specified rate of deformation of 0.05 inches per min. Less refined or homemade loading devices must be calibrated through experience to get the desired rate. For many soil specimens used in earth home construction, a loading rate of 500 pounds per minute will approximate 0.05 inches per minute deformation.

Tensile Test (ASTM Designation C190-58)

The specimens used in this test are molded into a briquet that can be pulled apart in a testing machine. Most specifications require a minimum strength in tension although design methods consider zero tensile strength. This test is used particularly for testing mortars and plasters.

Atterberg Limits (ASTM Designations D423-54T, D424-54T, and D427-39)

These tests are generally performed in a laboratory with the specially designed equipment illustrated in Figure 14. The tests may be performed in the field if weighing and drying facilities are available.

TABLE 3
The Heat-transfer Coefficients and Test Data for Earth Wall Specimens Are Given in This Table (National Bureau of Standards, Ref. 128)

	HT 13 Monolithic terracrete	HT 14 Monolithic terracrete	HT 15 Adobe block	HT 16 Bitu-dobe block	HT 18 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 (corrected for 15 mph outside wind)	0.79	0.64	0.54	0.53	0.54
Temperature difference, air to air	70.1	70.3	70.4	70.3	70.1
Thermal conductivity, k	12.0	15.2	10.7	10.4	11.3

Definitions:
u—number of BTU per hour transmitted through each square foot of specimen for each degree Fahrenheit difference in temperature between the air and the two sides, as observed under test conditions.
U—u corrected for a 15-mph wind outside and zero wind inside.
k—the thermal conductivity of the material.

The hand method of determining the liquid limit (AASHO designation T89-57) may be substituted for the standard liquid limit test. No modification is required for the plastic limit test. The linear shrinkage test (ASTM designation D427-39) may be substituted for the standard volumetric shrinkage limit test.

Absorption and Erosion Tests (ASTM Designations D915-47T par. 9, D559-57, D560-57)

The tests are performed similar to the field tests previously described. In the laboratory the equipment is somewhat more refined and laboratory control provides more consistent results. Typical laboratory equipment used in the tests is shown in Figure 15.

Special Soil Tests

Determination of Alkali and Soluble Salts

To determine the objectionable presence of alkali in a soil sample, fill a small, open mouthed glass container about one-half full of soil and add distilled water to bring contents to about two-thirds full. To this add a small amount of one-percent phenolphthalein. A purple coloration of the water will indicate the presence of alkali in the soil.

To detect carbonate salts, pour a small amount of hydrochloric acid on the soil. Effervescent action and voids or pits on the surface are indications of these soluble salts in the soil.

Full-Scale Wall Testing

To determine the strength properties of an earth wall, a full-scale wall can be constructed and tested in a large testing machine. The data obtained are primarily of interest to design engineers. Results of several such wall tests have been published by the U. S. National Bureau of Standards.[128]

STRUCTURAL REQUIREMENTS

General

The design of an earth-wall house differs little from that of a house built of other types of masonry. Floor plans, wall strengths, roofs, floors, and foundations must be designed to suit the particular climate, available building materials, and tenant requirements. In a few urban areas, standard building codes cover earth wall construction. Most of the construction to date has been based on local experience plus information obtained from various publications on the subject.

Walls

According to the majority of the literature, wall heights should be limited to two stories. The usually recommended wall thicknesses are 18 inches for two stories and 12 inches for one story. Little research has been reported that has studied the height-width ratios for the various types of earth walls. Authors have recommended a range of ratios from 8:1 to 18:1. Since 12 inches has become more or less a standard wall thickness, a normal 8-foot wall for one story produces a height to width ratio of 8:1.

The factors of safety that have been recommended with respect to strength vary from 10 to about 20. For example, a wall made from Landcrete blocks was designed for 11 pounds per square inch compressive strength although the wet crushing strength of the blocks was 230 pounds per square inch.[36] This wall was 9 inches thick and 9 feet tall, a height to width ratio of 12. Usually, an earth wall is designed for zero tensile strength, although some specifications require the tensile strength of the compacted soil to be at least 50 pounds per square inch.

Cross-sections for two adobe wall designs that have been successfully used for residential construction in Albuquerque, New Mexico, are shown in Figures 16 and 17. These designs illustrate the details of the concrete window sills and concrete parapet caps that are required to safeguard critical areas of the adobe walls from moisture entry and erosion.

Reinforcement

For block type construction, horizontal steel reinforcing rods spaced two or three feet apart may be placed in the mortar. No design criteria have been developed to determine whether this reinforcing is required. Vertical reinforcing may be desirable

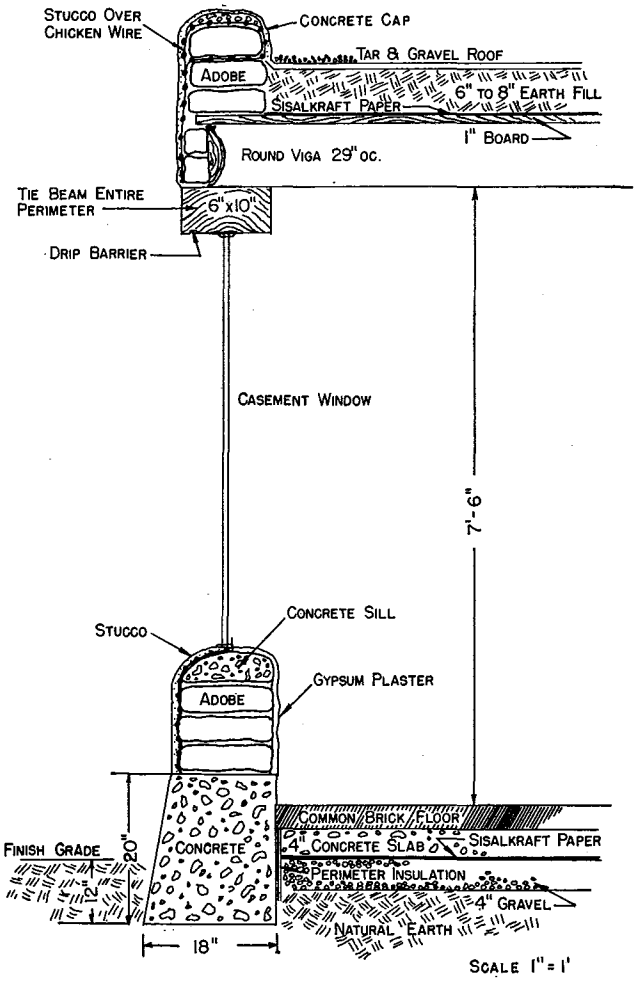


Figure 16. This typical wall section for adobe is used by Leon Watson and Associates, Albuquerque, N. M., builders of residential homes in this city.

but a suitable method of placing it has not been devised. For 12-inch walls made of a double row of interlocking 6-inch blocks, the vertical rods can be conveniently placed in the mortar between blocks. For other construction types the rods may have to be inserted in a drilled hole and then grouted in place.

Bond beams at the top of the wall are normally incorporated in the design. They serve two purposes, i.e., to reinforce the walls and to distribute the roof loads. They are made preferably from reinforced concrete, as shown in Figure 18, although timbers can be used. Some builders have reported using bond beams at several vertical intervals to improve the strength and alignment of the walls. This provision does not appear to be a necessity, particularly in stabilized soil construction.

Windows

The wooden window frames must be attached to the earth walls securely. Some builders nail the frames directly into the wall. A more satisfactory arrangement that can be suited to any construction method is practiced by Koeber, a builder in Albuquerque, New Mexico. In place of a building block a wooden nailer block (Figure 19) is inserted at window and door openings. This block becomes an integral part of the wall while furnishing an excellent support for the window or door frame. It is shown in place in Figure 20.

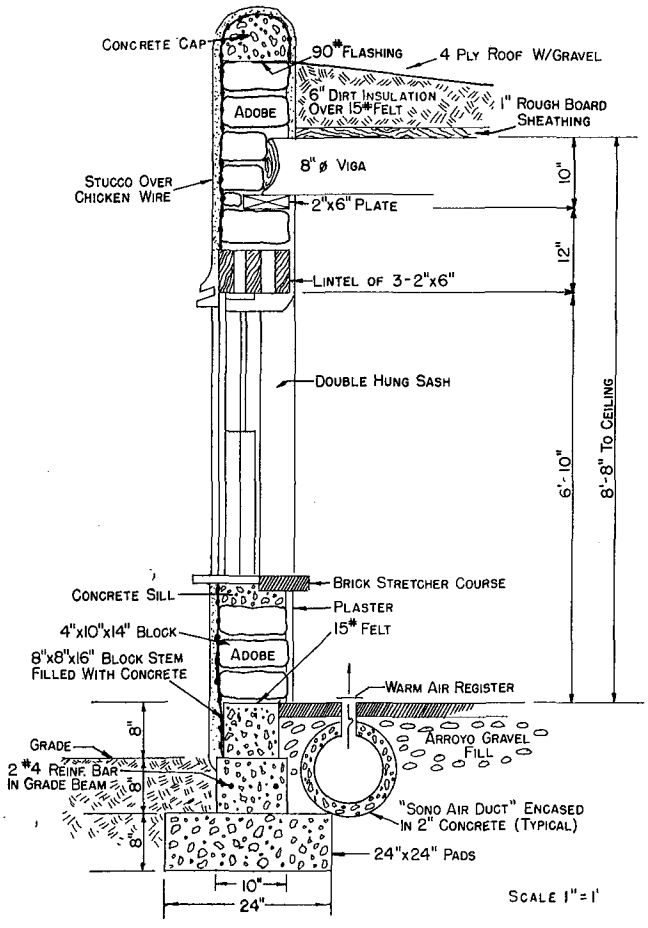


Figure 17. Another builder in Albuquerque, N. M., Robert C. Koeber, uses this wall section for adobe walls.

Lintels

Lintels are provided over every wall opening to prevent flexural distress in the wall above the opening. The lintel is made large enough to support construction stresses (especially in rammed earth construction) and the weight of the wall above. Usually a large timber or a reinforced concrete beam 6 inches or more in thickness is used. The lintel projects into the side walls at least the thickness of the wall. Figure 21 shows an early method of constructing lintels.

Several house designs have eliminated lintels by extending the window or door openings up to the bond beam.

Fireplaces

The details of a practical fireplace design offered by Watson of Albuquerque, New Mexico, are shown in a cross sectional view in Figure 22. The fireplace is situated in a corner of the room and in plan view approximates a circular arc at floor level. Noteworthy features of the fireplace include:

A. Downdraft deflector.

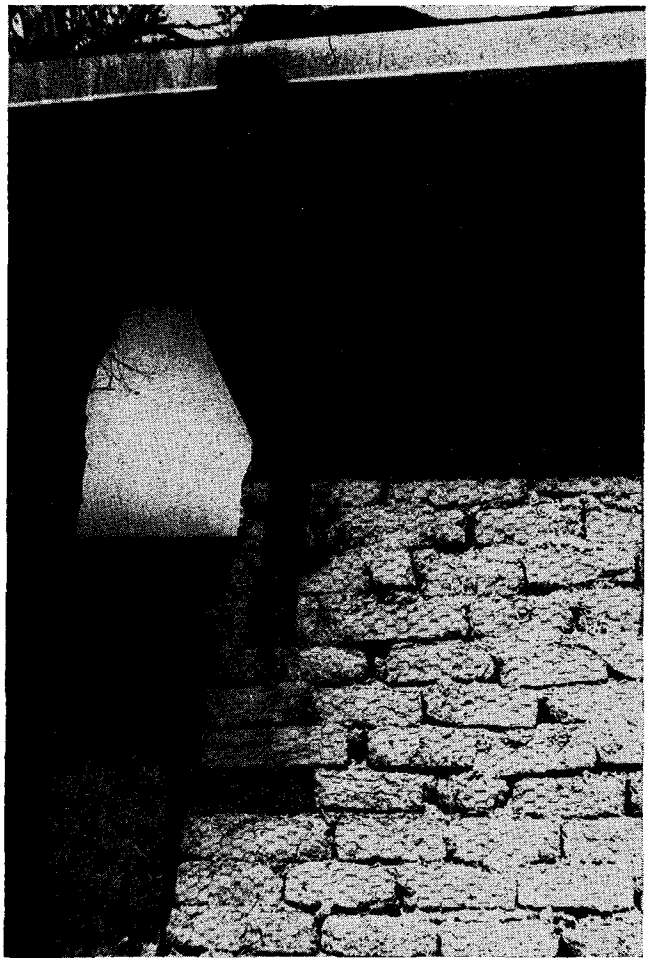


Figure 18. A concrete bond beam is used to reinforce this large, two story residence under construction in Albuquerque, New Mexico., (Koeber).

Figure 19. This 2" x 4" wood nailer block, of the same dimensions as an adobe block, is inserted in place of the adobe block around windows and doors to offer an excellent, rigid hanger for the window or door frame.

B. Expedient damper.
C. Simplified construction using forms.

The downdraft deflector is simply an arc at the bottom of the flue that returns the downdraft air to the channel of upward flowing hot air. The shield in front extends far enough down to prevent the downdraft from entering the room.

The damper is a light metal plate, approximately 8" x 20". It is hinged along the bottom edge to the inside of the front shield. A simple chain latch attached to the top of the damper extends through the front shield to allow the damper to be adjusted to the desired opening. The damper returns to the closed position by gravity.

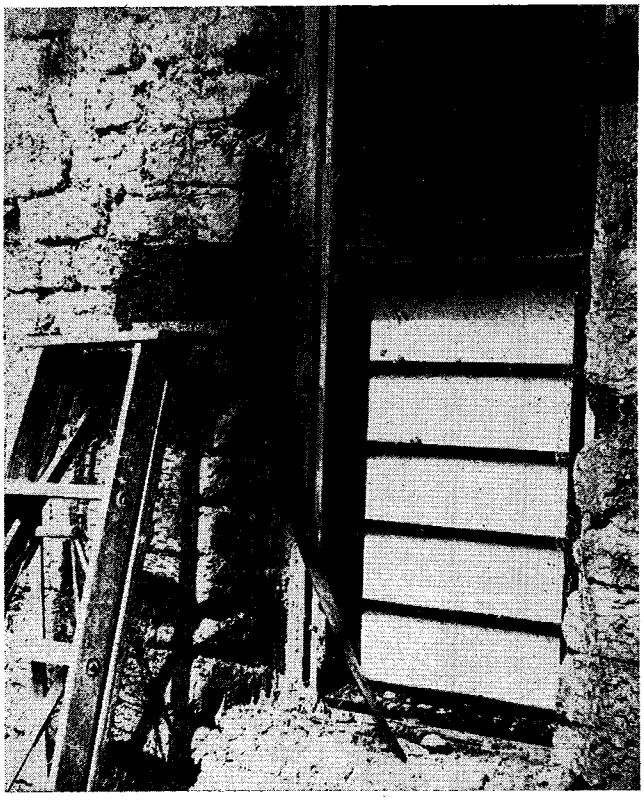


Figure 20. The nailer block in Figure 19 is shown in place (under the building paper) in this residence under construction in Albuquerque, N. M. (Koeber).

Figure 21. A cedar post was used as a lintel in this early construction at Ysleta, Texas.

The lower portion of the fireplace is built with either adobe blocks or fire bricks around wooden forms. The forms are shaped to the desired contour of the backwall of the fire chamber and they are re-usable. The chimney is formed by placing a cylindrical can, e.g., a milk can, at the position of the flue and laying blocks in mortar around the can. The can is slipped upward as the flue construction progresses. After learning the technique, a semi-skilled worker can construct a complete chimney in a few hours.

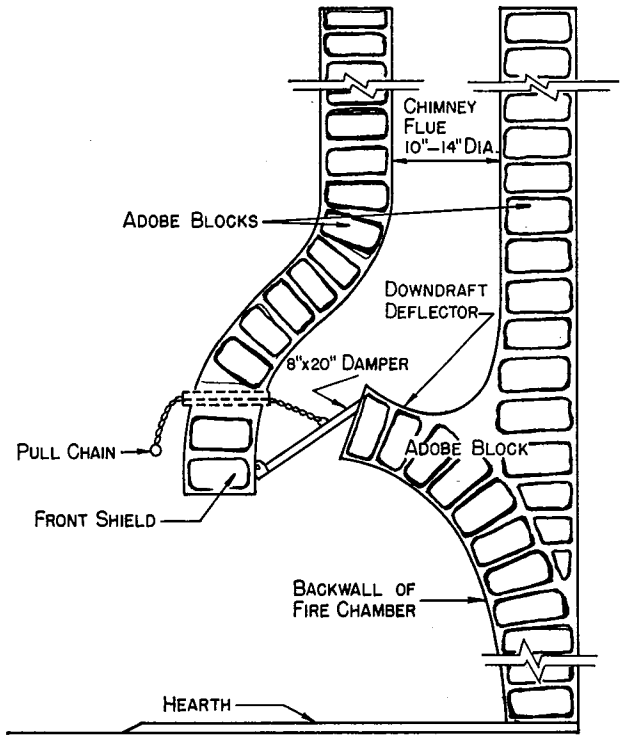


Figure 22. This simple design of an interior corner fireplace by Watson and Associates, Albuquerque, N. M., is practical as well as inexpensive.

Foundations

Three types of building materials have been used for the foundation footing walls: reinforced concrete, rubble and mortar, and stabilized soil bricks. The most satisfactory, but most expensive, is reinforced concrete. Probably the most common footing for low cost houses is made of rubble—old bricks, rocks, pottery, etc.—bonded with mortar. Stabilized soil bricks for below grade footings have been used recently, but performance records are not yet conclusive. Their use depends primarily on their ability to prevent capillary rise in the wall as well as supporting the loads when they are saturated.

Foundation walls should extend above grade to prevent splash damage to the wall. Most investigators recommend from 6 to 18 inches, but criteria have not been offered to compute the correct height above grade. Presumably, the required height is a function of the intensity of the rains, the length of the roof overhang, and the weather resistant properties of the earth wall.

Excessive loading of the subsoil can cause cracking of the walls due to footing settlement. An excellent example of a foundation failure is illustrated in Figure 23. Normally, soil exploration and testing of the subsoil is not available to compute safe bearing loads. Builders have often relied on the experience of other structures in the area plus their own judgment to determine the size of the footings. As a general guide, most shallow clayey and silty soils should not be loaded above one ton per square foot. On firm sand and gravelly soils, two to three tons per square foot may be used. For dry surface clays that are known to swell when wetted, it is advisable to extend the footings to a depth unaffected by seasonal moisture change.

Earthquake Resistance

In some areas, buildings must be designed to resist earthquake forces. Several specifications have been recommended[60] to provide the necessary stability. They are summarized below:

A. The plan of the building should preferably be compact and rectangular in order to minimize the effects of oscillations.
B. A substantial, one piece foundation is necessary. This is best obtained by monolithic concrete laid on a dense subgrade.
C. One story walls should be not less than 12 inches thick for exterior walls and 8 inches thick for interior walls. A two-story house should have 18- and 12-inch thick exterior and interior walls for the first story and light wood framing for the second story.
D. Integral reinforcement of the wall is advisable. Woven wire fencing should be placed in every fourth or fifth horizontal mortar joint and lapped at the corners. An improvement to this system, when a surface coating is to be applied, is to use a four- to six-foot width of one-inch wire mesh in every sixth joint. The extra width, which is turned down against the face of the wall and stapled to it, provides a good bond for the surfacing material.

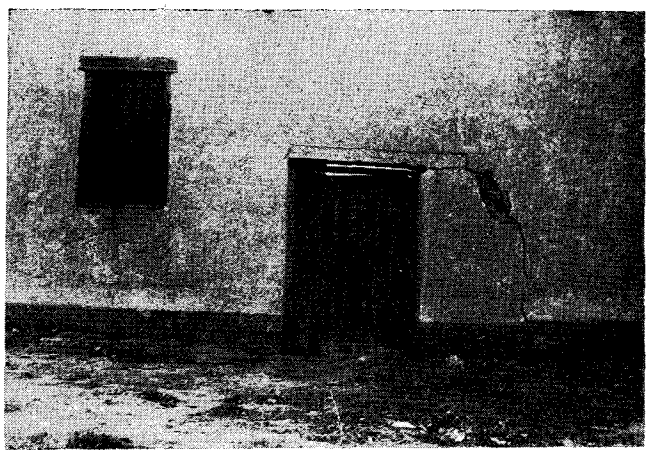


Figure 23. A soil bearing failure has caused structural cracks in the foundation footing wall and the adobe wall in this large community building.

E. Interior walls should be mounted on a foundation integral with the exterior wall foundation and should be similarly reinforced.
F. Partition walls of materials other than earth should be of light construction to avoid any rigidity that might crush or displace the earth walls during tremors.
G. A continuous reinforced concrete bond beam should be placed at the top of the earth walls.
H. The roof trusses should be designed to impart only compressive loads to the wall, and the roofs should be light.

Thermal Characteristics

The thermal characteristics desirable in house walls depend upon the climate. Very briefly, it can be stated that for single story dwellings the following approximations are reasonable.[36]

A. For cold climates, where room heating is required for an appreciable part of the winter season, heat transmission of the wall is important.
B. For hot, dry climates, where major discomfort is caused by excessive heat in summer, thermal capacity of a wall is important.
C. For hot, humid climates, comfort depends more on ventilation than on any other single factor. The thermal properties of the wall are of relatively minor importance.
D. In single-story houses the thermal characteristics of the roof will normally have far more effect on comfort than those of the walls.

Investigations of the thermal conductivities of various earth walls have been reported.[49,128] A partial report of results is shown in Table 3. Based on the conductivity per inch of thickness, earth walls conduct more heat than frame construction but less heat than concrete or fired brick. However, due to the large thickness of earth walls there is less total heat conductivity than in other types of walls. Normally, the only earth walls that might present a heat problem are thin walls made from high strength, dense blocks.

ROOFS AND FLOORS

Roofs

Any conventional form of roof construction can be used on earth wall houses. Thatched roofs are commonly used in many areas. In humid climates roofs of straw or grass must be replaced at frequent intervals due to deterioration. Earth, in the form of domes or vaults, earth tiles, and bunker fills, has also been used.

Since rain water can erode walls easily if allowed to channelize and run down the surface, eaves and roof overhangs are extended a sufficient distance to prevent this action.

Earth Domes or Vaults

In Egypt[78] mud block vault construction was used for roofs in a housing settlement at New Gourna. The principal features of the design are illustrated in Figure 24. These domes provide rooms with 12- to 13-foot clear spans. To reduce the number of walls that must resist the horizontal thrust of the domes, the rooms are aligned in rows so that only the two end walls resist the thrust. It may be uneconomical to build single-room units where all four walls must resist thrust for each dome.

The mud blocks used in this project were very similar to adobe. Due to the very arid climate, soil stabilizers were not used. This type of roof will be practical in humid areas only by incorporating waterproofing stabilizers in the blocks.

Earth Tiles

In India[61] sun-dried clay roofing tiles were investigated to determine their performance and cost. The tiles were made by packing a wet clayey mix into a form to make a 2" x 13" x 13" tile. Before placing the mix, thatch of about 5-foot length was placed in the bottom of the form, protruding in one direction. The resulting tile was a flat clay block with a 4-foot "tail" of thatch. To construct the roof, tiles were laid on a light timber frame with the thatch extending down the slope. This construction is illustrated in Figure 25. The clay tile provides strength and repels water while the thatch provides insulation as well as a protective covering for the clay tile.

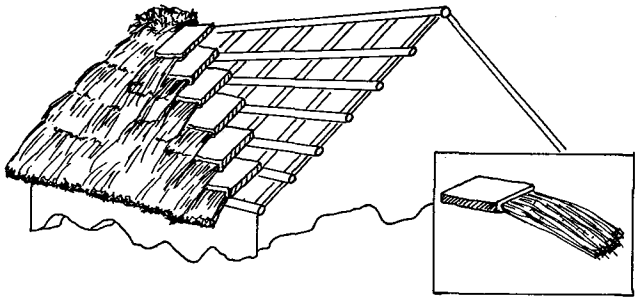


Figure 25. A thatched-earth tile roof of this design proved successful in research studies in India.

The cost of this roof is about the same as for a flat mud roof or a burnt clay tile roof, but it has an advantage in very low maintenance and low heat conductivity.

Bunker Fills

A bunker fill or flat mud roof has been widely used as a low cost roof. The main expense in this roof is the heavy timbers (vigas) required to support the load of several inches of earth fill. Unless overlaid by a protective covering, this type of roof is subject to considerable maintenance since the earth fill develops cracks and is in constant need of patching after rains. In some tropical areas this roof is attractive due to the abundance of timber and the availability of certain types of very stable lateritic soils. Alternatively, lime stabilized soils have been rammed in place to produce a dense, durable roof.

A cutaway illustration of the bunker fill roof is shown in Figure 26. Figures 27 and 28 point out the interior details of the vigas and the ceiling construction.

Floors

For the more expensive construction, concrete slabs and wooden structural floors may be used in the conventional manner. In some humid areas

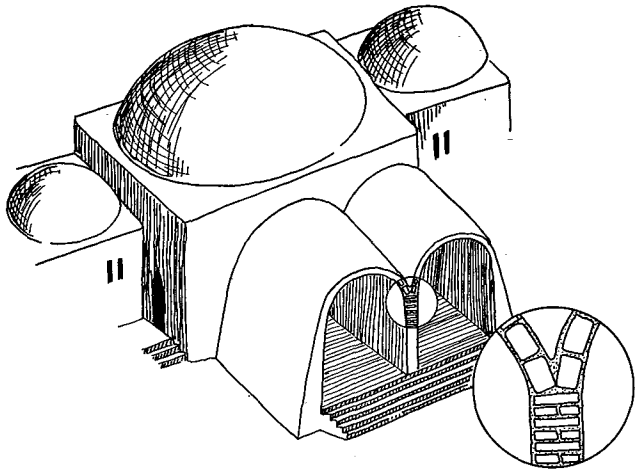


Figure 24. This style of earth dome and vault construction was used in a reconstruction program at New Gourna, Egypt.

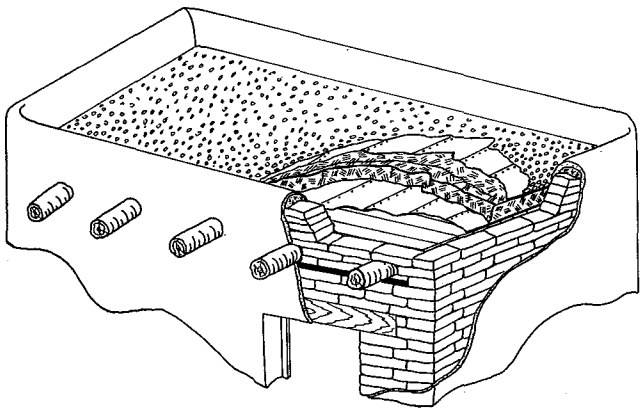


Figure 26. The cutaway section of this bunker fill roof shows the layered structure of the roof. From the top down, the components are gravel and asphalt, building paper, earth fill, building paper, wood sheathing and supporting beams (vigas).

Figure 27. The large and small ends of the ceiling timbers (vigas) are alternated to provide a balanced appearance.

where white ants (termites) are active, wooden structural floors may be short lived.

The expensive types of floors are not necessary for the majority of home builders. Properly compacted stabilized earth or high strength stabilized blocks can provide a very durable and attractive floor. Practical experience has shown that a stabilizing admixture is usually required in floors. Even the most primitive dwellings have some type of oil, fat, or other admixture in the floor.

Usually earth floors are underlaid by a granular base material that not only provides drainage but also blocks capillary moisture rise. Since the floor is usually less than three inches thick, a high quality mix can be used economically.

In India[61] a floor of soil-cement with five percent cement by weight compacted to a thickness of three inches and followed by a rendering of neat cement paste was found to be the most desirable from the standpoint of economy and durability. This floor was placed over the natural soil, which had been cleared of vegetation and compacted.

To control the crack pattern and improve the appearance of the finished floor, it should be built in sections about three feet square. In this connection the cracking in soil-cement floors can be minimized by a proper curing period of about two days to a week. Moist straw or rags covering the floor will provide good curing.[135]

CONSTRUCTION OF EARTH HOMES

General

Five methods of construction defined in the second section will be discussed here. They are:

A. Cob.
B. Wattle and Daub.
C. Adobe.
D. Rammed Earth.
E. Machine-made Blocks.

Where the information is available and applicable, these methods will be discussed with respect to procedures and techniques, construction equipment, production rates, and relative unit costs.

Figure 28. To compensate for the unevenness of the tops of the vigas, saplings can be placed diagonally for sheathing. Note the straw used in this case to prevent the earth fill from sifting through the ceiling.

Cob

This method requires a minimum of construction equipment. Invariably, the soil mix is prepared in a pit or pile with mixing being accomplished by treading. Compaction is performed by hand, eliminating the need for tampers. Forms are not used to control the wall surfaces; instead the walls are trimmed to the desired thickness.

After the soil mix in the pit has reached the desired consistency and uniformity, balls of the mix about the size of footballs are formed. These are placed in the wall and pounded into place by hand. The moisture content is lower than used for adobe, but higher than for rammed earth. Each course is allowed to dry and shrink for about two or three days before the next course is laid. Wall faces are pared off with a knife or stick and worked smooth. As the height of the wall increases, the workman sits astride the wall and balls of earth are thrown up to him, eliminating the need for scaffolding.

Essentially, this construction can be accomplished by one workman, using only occasional part-time help. Earth digging and replenishment of the prepared mix can be done by another workman. The work is rather slow, due to the time required for each course to dry; therefore the high production rate that could be accomplished by several workmen is not practical.

Wattle and Daub

Like cob, this method requires a minimum of construction equipment. Mixing is easily accomplished by hand or by treading. Forms are not used, compaction equipment is not required, and scaffolding is optional.

Normally, two workmen are needed to erect the framework of posts and brushwork. After the framework is in place, the prepared mix, in the form of a workable plaster, is applied to both sides of the framework. Shrinkage cracks that occur are filled with the same mix until the wall is stable. Unless stabilized or covered with a weather resistant surface coating, the maintenance of this wall is continuous.

Adobe

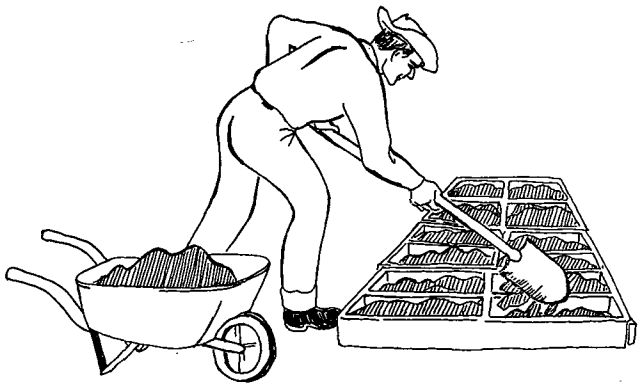
Adobe construction has been discussed at length in numerous reports. The common hand or primitive method of blockmaking, as illustrated in Figures 29a through 29e, has received the attention of most authors. Several improvements on this primitive method have placed adobe on a competitive basis with other types of earth construction. Mechanical mixing methods shown in Figures 30a and 30b have been devised to increase production while efficient production lines have been utilized to lower the unit cost of the blocks. For very large scale projects, molding machines have been developed that will extrude the mix at the proper cross-section and cut the blocks to the desired lengths.

For low investment, single-unit projects, the primitive method is still widely used. The only construction equipment involved is forms and pallets. The forms may be made for a single block, although forms for two or four blocks are usually made. The usual thickness of blocks is four to six inches. Depths conform to the desired thickness of the wall, usually 9 to 18 inches. The length is a function of the weight of the block since a 50-pound block is about the maximum weight that can be conveniently handled. Two convenient sizes are 5″ x 10″ x 20″ blocks (approx. 55 pounds) and 4″ x 12″ x 18″ (approx. 50 pounds).

An outstanding limitation of adobe construction is the curing of the blocks. The usual curing procedure is as follows (Figures 31a and 31b).

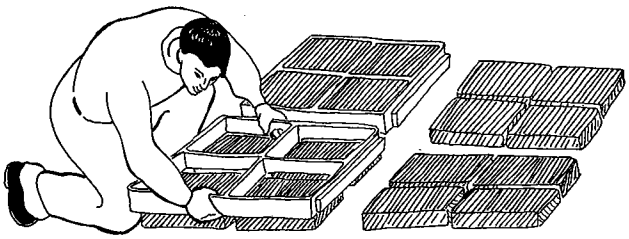
A. After the prepared mix has been hand tamped into the form, the form is immediately removed. The new block remains in place from two to four days while it gains strength.
B. When the blocks are strong enough to pick up, they are placed on edge to finish curing. The final curing takes a minimum of three weeks. (If a stabilizer such as lime or cement is used, the blocks are initially covered with wet straw or cloth and not turned on edge for seven days.)
C. At the end of the curing period, the blocks are stacked to reduce storage area requirements.

As a result of the long curing period, considerable area must be available for storage. During dry,

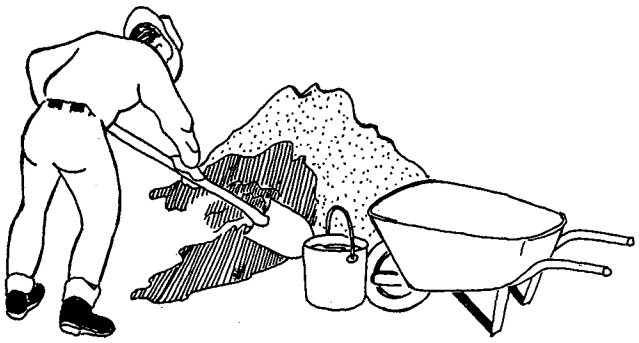


b. Charging the forms.

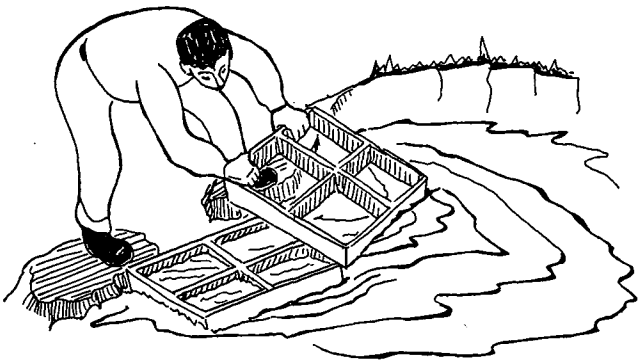
c. Kneading and leveling the blocks.



d. Lifting the forms from freshly made blocks.



a. Preparing the soil mix.



e. Washing forms for next cycle.

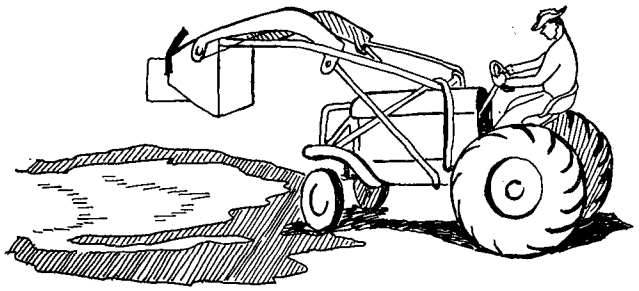
Figure 29. The steps in making adobe blocks by the manual method.

hot seasons, the curing can be accomplished without a protective roof, but if rain is expected a protective covering is needed. The blocks shown in Figure 32 were ruined by rain because no protective measures were taken. Certainly, if the cost of a large protective shed must be added to the construction costs, the unit cost of the blocks will be very high. Less expensive protection, such as plastic films, may be practically used.

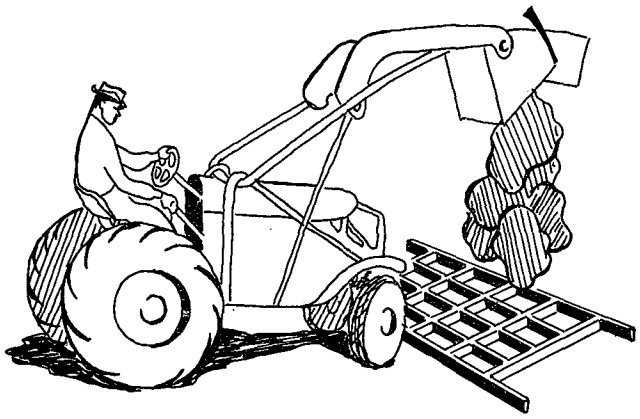
The blocks must be placed in the wall with a suitable mortar. It is desirable to use a jointing mortar which is not appreciably stronger than the blocks themselves. This enables small movements to be accommodated in the joints without causing general cracking through the blocks. For most purposes, a mix of 1:2:8-9 of portland cement, hydrated lime, and sand is recommended for the mortar. If lime is not available, the same soil mix used in the blocks can be utilized as a substitute. Experimentation with the mortar may show that even higher percentages of the soil mix are suitable. For instance, the Trass soils of the Rhine Valley and certain deposits in Java react so well with lime that the portland cement and sand are not needed to form a good mortar.[36]

Rammed Earth

Rammed earth walls are made by tamping moist soil into forms. The walls are rammed directly upon the foundations in sections. After a section is completed, the forms are shifted laterally (or vertically) to contain the next section.



a. Front end loader is used to mix soil with water in large sump.



b. Machine transports prepared soil mix to multi-forms.

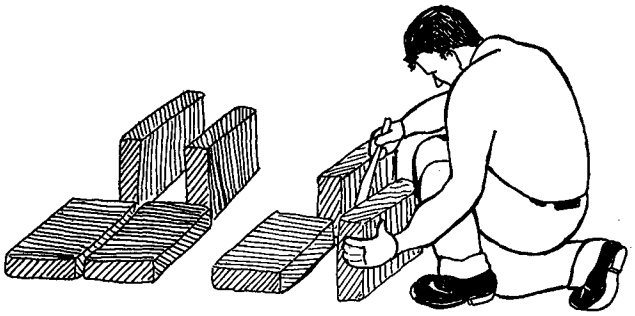
Figure 30. Machine method of making adobe blocks.

The forms are similar to those used in concrete construction. They are usually made of about two-inch thick lumber and are designed to contain a section of the wall approximately two feet high and 8 to 16 feet long. Thinner form lumber may be used if the forms are adequately braced. An example of ¾ inch plywood forms is shown in Figure 33.

The soil mix used in this method of construction is carefully selected and combined to obtain a high initial strength and a minimum of shrinkage. This allows a rapid construction schedule that can utilize an efficient team of workmen. In areas of short duration of favorable weather, this scheme is advantageous. A typical high production team might be composed of the following four workmen:

A. One worker to tamp the mix in the forms.
B. One worker to charge the form with the prepared mix.
C. Two workers to dig the soil and prepare the mix.

Obtaining the correct moisture content is a sensitive element in mix preparation. An optimum moisture content exists for any given mix and amount of tamping that will give the highest strength for the wall. To obtain good results, the moisture content of the mix must be controlled to within ±2 percent of the optimum. With some mixes, however, experience on the job might indicate that this total per-



a. Unstabilized block is turned on edge to dry after two to four days

b. Cured block is stacked after three weeks.

Figure 31. The curing schedule for adobe blocks.

Figure 32. Inadequate protection of blocks during curing schedule may result in a loss such as occurred here after a rainstorm.

mitted variation of 4 percent should be mostly on the dry side or the wet side of optimum.

An efficient aid in modern rammed earth construction is the use of pneumatic tampers. For multi-unit projects, this equipment is invaluable in maintaining accelerated work schedules and uniform ramming. This allows the utilization of more workers in the soil mix preparation stage.

To assure a minimum standard performance in the completed wall, test specimens must be taken as the job progresses. They may be taken in two ways. In one instance, test blocks approximately four inches square by eight inches long (minimum) may be carved from a completed section of wall. The damaged area is carefully repaired immediately after the sample is taken. A more convenient method uses specially constructed forms of the desired test specimen size. At intervals, the soil mix is taken from the regular batches and tamped into these molds in the same manner as in the wall forms. These specimens are tested to determine the quality of the wall section.

The forms used in rammed earth are of two general types:

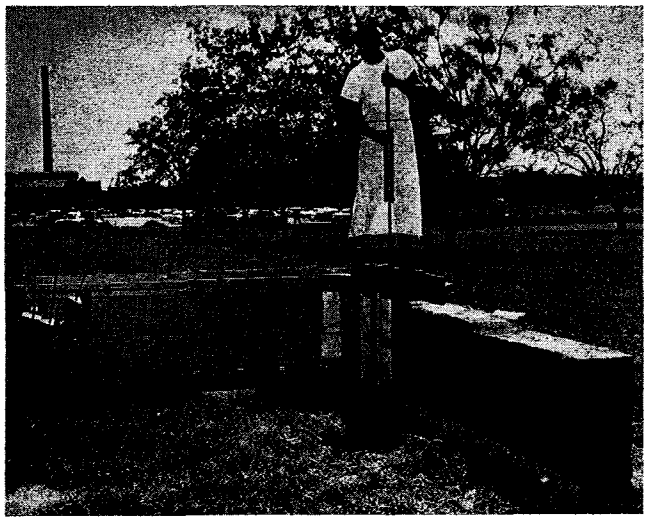


Figure 33. An experimental sliding weight hammer is used in this test wall of rammed earth.

A. Those using a tension rod at the bottom of the form which projects through the completed wall section.
B. Those using a compression bar above the completed wall section with nothing projecting through the wall.

Diagrams of these two types are shown in reference 36 (p. 69). A modification proposed by Middleton[75] incorporates rollers on the front and back of the form to facilitate movement and alignment. Middleton's diagrams do not show a vertical adjustment to be made in the position of the rollers, but such an adjustment would be desirable on at least one end.

Additional forms should be available to allow monolithic construction of corners and tees.

The construction of the hand tampers is an important consideration. In general, the tamper should be heavy enough to produce suitable compaction of the mix, but should be light enough to prevent undue fatigue of the operator. Based on the various weights, contact areas, and contact shapes that have been reported, it appears that the average tamper in use has a square face approximately 3 x 3 inches and weighs from 16 to 20 pounds. Metal construction has been recommended, particularly for the face of the tamper.

Machine-Made Blocks

Equipment

Several hand and power driven machines have been developed in recent years to provide high strength, uniform earth blocks using soil mixes similar to those used in rammed earth. Machines that have been reported in use to date are the Landcrete, Winget, Ellson, and CINVA-Ram.

The Landcrete, manufactured by Messrs. Landsborough Findlay (South Africa) Ltd., Johannesburg, is a hand operated toggle press which has been developed specifically for the manufacture of blocks and bricks with stabilized soil. It is a well designed machine, very sturdy in construction and simple and convenient to operate.[36] The manufacturer claims a power driven model of the Landcrete makes at least 500 bricks per hour as compared with the 100-150 of the hand operated machine. On-the-job performance records of this machine have not been obtained. The various shapes of blocks molded by this machine are illustrated in Figure 34.

The Winget machine (Figure 35) is a hydraulic press powered by a gasoline engine. It is made by Messrs. Winget Ltd., Rochester, England. It has a rotating table with three operating positions for mold filling, pressing, and ejecting. This table is rotated manually so that the rate of production is controlled by the operators. Owing to the high operating pressures (1000-1200 psi), the quality of the blocks produced is good, but the rate of production is the same as for a hand operated machine.

The Ellson Blockmaster is a manually operated blockmaking machine manufactured by Ellson Equipments (Pty.) Ltd., Johannesburg, South Africa. Through the use of interchangeable molds, it produces either 9" x 12" x 4" or 6" x 12" x 4" blocks. Other molds and attachments are available to form inter-

locking blocks, 4½" x 9" x 4" bricks, or 18" hollow bricks. The machine operates on a toggle switch lever system (Figure 36) which gives a constant length stroke, thereby standardizing the thickness of the blocks. The effective lever ratio is approximately 500:1. The manufacturer claims a production rate of 900 to 1100 blocks per eight-hour day, and a rate of 1400 to 1600 blocks per day with a semi-automatic loader attached. The production rate for bricks is approximately doubled since two bricks are made in one operation. Weight of the complete machine, less spare molds, is approximately 485 pounds.

The CINVA-Ram blockmaking machine was developed by the Inter-American Housing and Planning Center (CINVA) at Bogota, Colombia, in 1952. It is now manufactured in the United States by Richmond Engineering Co., Richmond, Va. The CINVA-Ram operates on the principle of an infinitely varying lever arm which develops high pressures on the blocks. It is manually operated, lightweight (approximately 100 pounds) and relatively maintenance-free. Standard block size produced by the machine is 3½" x 5½" x 11½". An attachment is also available to make 1½" thick blocks which are suitable for floor and roof tiles.

Procedures for using the CINVA-Ram are shown in Figures 37a, 37b, and 37c.

Although a housing project was built using this machine, recent reports on the condition of the houses in this project are not available. A comprehensive testing program was accomplished during the development of the machine, and important results were published in **Civil Engineering,** December, 1952.[120] This report indicates that excellent results may be obtained with the machine. Production figures and probable unit cost estimates were not included in the report.

At present a research project underway at the University of California includes the use of the CINVA-Ram. The project concerns the effects of pressure and varying amounts of sand and cement on the strength and absorption of earth blocks. Again, production figures and unit cost estimates have not been reported.

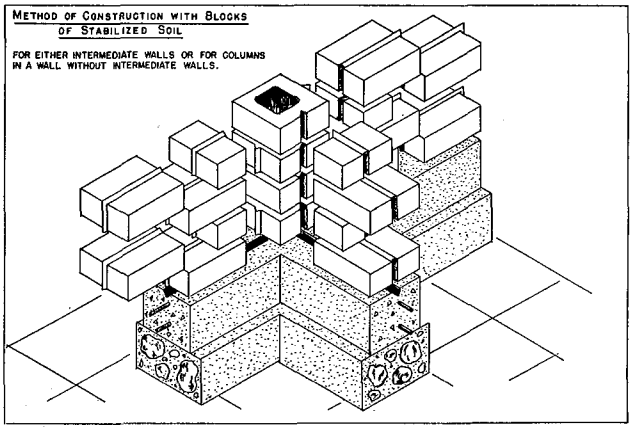


Figure 34. The various shapes of blocks produced by the Landcrete block-making machine allow rigid construction of corners and tees.

Figure 35. This Winget rotary block-making machine is being used in the British Cameroons.

Construction

The placement of machine-made blocks in the wall is quite similar to that used in burnt brick and cement block construction. Uniformity of block size permits a creditable blocklaying job. Also, the higher strength of the blocks necessitates a good lime-cement mortar for best results. Stabilization and/or surface coatings may be used based on experience of previous buildings in the area and the severity of the weathering. The use of stabilization will result in a first-class, permanent structure.

Winget manufacturers[119] have reported that six-inch thick walls are adequate for permanent construction; however, the thermal characteristics of such a wall would require investigation.

Relative Unit Costs

Complete data are not available to make a thorough comparison of the costs of each method of construction. Obviously, some methods (cob, wattle and daub) require almost no investment funds and

Figure 36. The compression and ejection stroke with this Ellson block-making machine consumed 1.4 seconds by stop watch.

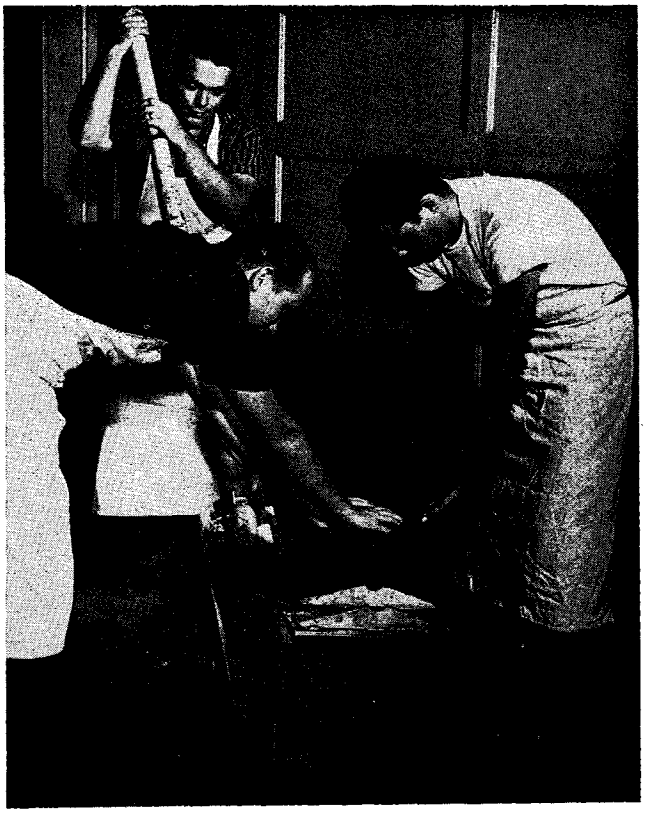
no labor requirements outside of the builder's family. However, a large amount of the family's time will be consumed, particularly in subsequent maintenance.

The primitive method of unstabilized adobe is another example of a method that requires little financial investment from the tenant family. Some information on unit costs is available for modern stabilized adobe, rammed earth, and machine-made blocks. Fitzmaurice[36] has collected data from several world-wide sources on the costs involved and has attempted a comparison. His table is prefaced by the following remark:

> "It is notoriously difficult to compare costs of building operations carried out by different contractors on different sites. Efficiency of organization contributes greatly to the results obtained, and this varies from site to site. The skill of the operatives and the amount of effort that they put into their work are also extremely variable. Consequently, the data that are assembled . . . must inevitably be taken with considerable reserve, and the real validity of the comparisons attempted are highly questionable."

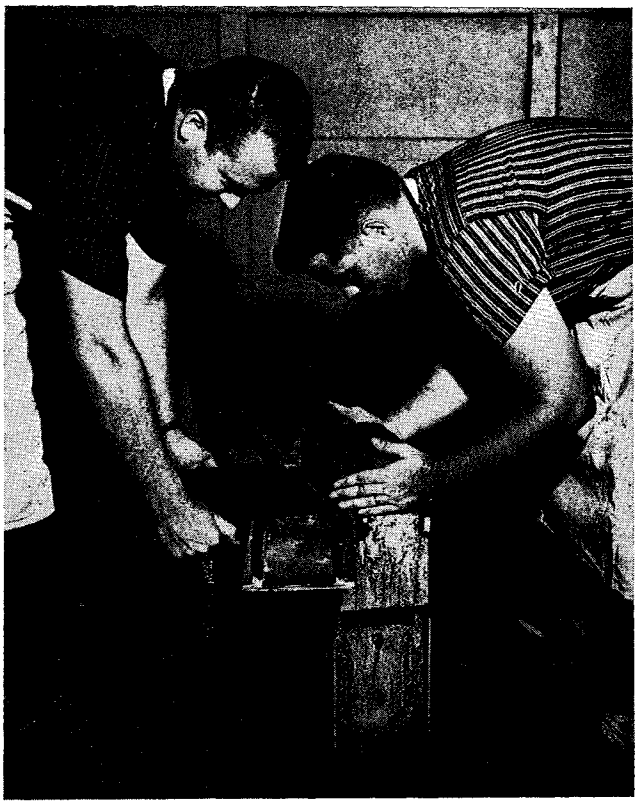
TABLE 4
Costs of Stabilized Soil Walling

Construction	Country	Cost per 100 Cu. Ft.	Authority
Rammed in place, 4% cement	Ceylon	$12.90	Middleton
Landcrete bricks, 5% cement	India	$16.20	Mahra
1:7 Cement: Sand Mortar			Chadha Aggarwal Wason (Ref. 21)
Soil Cement Blocks (equal to 2 bricks in size)	St. Vincent	$19.70	Colonial Building Notes
Stone Masonry		$25.90	D. S. I. R.
Concrete		$30.30	U. K.
Soil Cement Blocks	Gold Coast	Saving of 15-20% compared with cement-sand blocks or burnt-bricks	Alcock (Ref. 96)



a. Charging mold box with soil mix.

b. Pressure stroke.



c. Extrusion of finished block and removal to curing area.

Figure 37. Three principal steps in production of hand operated block-making machine (CINVA-Ram).

Fitzmaurice has also approached the comparative costs of various stabilized soil walls in another way. He has computed the amount of labor per cubic foot of wall for each method. This information can be applied in any community at the prevailing wage rates to get the comparative labor costs.

The economics of any type of construction are an involved process that must be considered by the builder for the prevailing set of circumstances. In some under-developed countries, for instance, the soil stabilizing medium may represent more than half the cost of the project. Certainly, in this case, the smallest fractional percent of admixture that will contribute the desired results should be specified. In other areas, labor costs for earth construction may be so high as to place the project in dubious competition with conventional building methods.

In view of the intangibles involved, no valid generalization can be made regarding the comparative unit costs of the various construction methods.

PRIMARY BIBLIOGRAPHY

1. *Adobe Brick.* Agricultural Engineering Yearbook, p. 130, 1959.
2. *Aided Self Help in Housing Improvement.* Ideas and Methods Exchange No. 18, International Housing Activities Staff, U. S. Housing and Home Finance Agency, Washington 25, D. C., Revised November, 1956.
3. Alcock, A .E. S. *How to Build to Size and Shape.* New York: Longmans, Green and Co., 1958.
4. Alcock, A. E. S., "Soil Stabilization as Applied to Traditional Building Methods in the Tropics," *Builder,* Vol. 175, p. 283, September 3, 1948.
5. Atkinson, Anthony G., "Design and Construction in the Tropics," Housing and Town and Country Planning, Bulletin No. 6, United Nations, New York, p. 7, January, 1952.
6. Barre, Henry J. *The Relation of Wall Construction to Moisture Accumulation in Fill-Type Insulation.* Iowa State College, Agricultural Experiment Station Research Bulletin No. 271, April, 1940. (Note: No direct references to earth walls. However, general principles of moisture accumulation, discussed in this article, will apply to earth construction.)
7. Baver, L. D., "The Effect of Organic Matter upon Several Physical Properties of Soils," *Journal of the American Society of Agronomy,* Vol. 22, p. 703, 1930.
8. Baver, L. D., and Hall, N. S. *Colloidal Properties of Soil Organic Matter.* University of Missouri Agricultural Experiment Station Research Bulletin No. 267, 1937.
9. Bee, R. J., "The Application of Engineering Research to Tropical Problems," (Singapore) United Nations, p. 24, 1950.
10. Bertramson, R. R., and Rhodes, H. F., "The Effects of Cropping and Manure Applications on Some Physical Properties of a Heavy Soil in Eastern Nebraska," *Proceedings Soil Science Society of America,* Vol. 3, p. 32, 1938.
11. Batts, M. C., and Miller, T. A. H. Rammed Earth Walls for Buildings. Farmers Bulletin No. 1500, U. S. Department of Agriculture, 1937.
12. Biggs, Charles, and Causing, Humbert. "The Application of Soil Stabilization to Low-Cost Housing." M.S. Thesis in Engineering, Princeton University, Princeton, New Jersey, 133 pages, date unknown.
13. Bouyoucos, G. J., "A Comparison of the Hydrometer Method and the Pipette Method for Making Mechanical Analyses of Soils with New Direction," *Journal of the American Society of Agronomy,* p. 747, 1930.
14. Bouyoucos, G. J., "The Hydrometer as a New Method for the Mechanical Analysis of Soils," *Soil Science,* p. 343, May, 1927.
15. Bouyoucos, G. J., "The Hydrometer as a New and Rapid Method for Determining the Colloidal Content of Soils," *Soil Science,* p. 319, April, 1927.
16. Bouyoucos, G. J., "Making Mechanical Analyses of Soils in Fifteen Minutes," *Soil Science,* p. 473, June, 1928.
17. Burkhart, Edsel J. *Investigation of Soils and Building Techniques for Rammed Earth Construction.* A. & M. College of Texas, Engineering Experiment Station Research Report No. 6, 1949.
18. *Burma Mission's Experience with Stabilized Earth Block.* Ideas and Methods Exchange No. 19, International Housing Activities Staff, U. S. Housing and Home Finance Agency, Washington 25, D. C., October, 1954.
19. Burmeister, R. A., "Sulphite Liquid as a Road Binder Material," *Public Works,* Vol. 90, No. 4, p. 130, April, 1959.
20. Burrows, Blair Action. *Building with Mud, Rammed Earth or Pise de Terre.* Ontario Department of Lands and Forests, Toronto, Canada, 46 pages, n.d.
21. Central Road Research Institute, "A Brief Report on the Working of 'Landcrete'—a Brick Making Machine." (A mimeographed report, unnumbered and undated.) 3 pages.
22. *A Cheap Coating of Unstabilized Earth Walls.* Ideas and Methods Exchange No. 2, Item J, International Housing Activities Staff, U. S. Housing and Home Finance Agency, Washington 25, D. C., December 8, 1952.
23. *A Cheap Hard Floor of Earth Stabilized with Portland Cement.* Ideas and Methods Exchange No. 1, International Housing Activities Staff, U. S. Housing and Home Finance Agency, Washington 25, D. C., November, 1952.
24. "La Construction en Beton de Terre," Bureau Central d'Etudes pour less Equipments d'Outre—Mer, Service de l'Habitat, 66 pages, Paris, 1952.
25. Crawford, P. H., "Soil Cement Bricks: Their Various Uses," *South African Municipal Magazine,* Vol. 39, No. 480, August, 1957.
26. Cytryn, S. *Soil Construction, Its Principles and Application for Housing.* Ministry of Labor, Housing Division, State of Israel, December, 1956, 183 pages.
27. Davidson, D. T., and Ewing, C. B., Jr. *Application of Cement Stabilized Soil to One Story Building Construction.* Iowa State College: Department of Civil Engineering, Engineering Division, 1957. 66 pages.
28. Day, Michael, "You Build Your Next House of Molasses," *Popular Mechanics,* p. 110, September, 1951.
29. Delong, H. H. *Rammed Earth Walls.* South Dakota State College, Agricultural Experiment Station Circular 149, April, 1959. 20 pages.
30. *Earth for Homes.* Ideas and Methods Exchange No. 22, International Housing Activities Staff, U. S. Housing and Home Finance Agency, Washington 25, D. C., March, 1955.
31. *Earth Manual—A Manual on the Use of Earth Materials for Foundation and Construction Purposes.* U. S. Bureau of Reclamation, Denver, Colorado, 1951. 332 pages.
32. "Earth Wall Construction,"
    Part I "Choice of Soil and Methods of Construction." No. SB 13, undated.
    Part II "Rammed Earth," No. SB 18, June, 1951.
    Part III "Adobe Blocks (Puddled Earth)," No. SB 20, undated.
    Part IV "Stabilized Earth," No. SB 22, March, 1952.
    All 4 publications are *Notes on the Science of Building.* Chatswood, N. S. W., Australia: Commonwealth Experimental Building Station, Department of Works and Housing.
33. Evans, L. T., "Structural Adobe," *Engineering News-Record,* Vol. 122, p. 498, April 13, 1939.
34. Eyre, Thomas T. *The Physical Properties of Adobe Used as a Building Material.* University of New Mexico Engineering Bulletin No. 263, 1935.
35. Fenton, F. C. *Use of Earth as a Building Material.* Kansas State College, Engineering Experiment Station Bulletin No. 41, 1941. 34 pages.
36. Fitzmaurice, Robert. *Manual on Stabilized Soil Construction for Housing.* Technical Assistance Program, United Nations, New York, 1958. 125 pages.
37. Fitzmaurice, Robert, and Rosenak, S. *Experiments on Stabilized Soil Wall Construction in Burma.* Technical Assistance Administration, United Nations, New York, 1956.
38. Gallaway, Bob M., "Rapid Preparation of Soil Samples," *Excavating Engineer,* p. 25, May, 1952.
39. Gallaway, Bob M., and Buchanan, Spencer J. *Lime Stabilization of Clay Soil.* A. & M. College of Texas, Engineering Experiment Station Bulletin No. 124, January 1, 1951.

40. Glenn, H. E. *Rammed Earth Building Construction.* Clemson College, Engineering Experiment Station Bulletin No. 3, 1943. 18 pages.
41. Hansen, Edwin L. *Suitability of Stabilized Soil for Building Construction.* University of Illinois, Engineering Experiment Station Bulletin No. 333, 1941. 40 pages.
42. Harrington, E. L. *Adobe as a Construction Material in Texas.* A. & M. College of Texas, Engineering Experiment Station Bulletin No. 90, 1945.
43. Hennes, Robert G. *Stabilized Earth Blocks for Protective Construction.* University of Washington, Engineering Experiment Station Bulletin No. 111, April, 1959. 24 pages.
44. Horn, Louis J., "Utilizing Earth as a Quantity Construction Material," *Texas Engineering Experiment Station News,* College Station, Texas, p. 3, March, 1952.
45. Housing Bulletin No. 2 of the Albert Farwell Bemis Foundation Massachusetts Institute of Technology, Cambridge, Mass., including:
    1. "Solidification of Soil by Means of Chemicals," Supervisor, Professor T. William Lambe.
    2. "Stabilization of Soils with Calcium Acrylate," Reprint from *Journal of the Boston Society of Civil Engineers,* Vol. 38, No. 2, April, 1951.
    3. "The Stabilization of Soils by In-Situ Polymerization," Presented before the American Society of Civil Engineers in New York, October 26, 1951.
46. "Housing in Pise De Terre," Report by the National Building and Housing Board to the Secretary, Office of the High Commissioner for Southern Rhodesia, Salisbury, Southern Rhodesia, date unknown.
47. How to Prepare Waterproof Mud Plaster. Ideas and Methods Exchange No. 23, Item D, International Housing Activities Staff, U. S. Housing and Home Finance Agency, Washington 25, D. C., March, 1955.
48. Hurtubise, Jacques E., "Sulphite Liquor as a Stabilizer," *Roads and Engineering Construction,* Toronto, Canada, p. 190, November, 1952.
49. Hutcheson, N. B., and Ball, W. H., "Thermal Conductivity of Rammed Earth," Report of Housing Research Committee, College of Engineering, University of Saskatchewan, Canada, (duplicated document), date unknown.
50. *Hyderabad Engineering Research Laboratories Annual Report, 1948.* The Hyderabad Laboratories, India, Government Press, 1949. 217 pages.
51. *Hyderabad Engineering Research Laboratories Annual Report (Technical), 1949.* The Hyderabad Laboratories, India, Government Press, 1950. 259 pages.
52. *Investigation of the Unconfined Compressive Strength of Soil-Cement Mixtures.* U. S. Waterways Experiment Station, Vicksburg, Mississippi, Technical Memorandum No. 187-1, February, 1942.
53. Johnson, A. Morgan, "Laboratory Experiments with Lime-Soil Mixtures," Proceedings of the 28th Annual Meeting of the Highway Research Board, Washington, D. C., December, 1948.
54. Johnson, S. L., Dear, P. S., and Whittemore, J. W. *Adhesion of Plaster, Stucco, and Mortar to Various Structural Backings.* Virginia Polytechnic Institute, Engineering Experiment Station Bulletin No. 68, July, 1948.
55. Kirkham, John Edward. *Development of Earth Building Blocks.* Oklahoma A. and M. College, Engineering Experiment Station Publication No. 46, 1940. 15 pages.
56. Kirkham, John Edward. *How to Build Your Home of Earth.* Oklahoma A. and M. College, Engineering Experiment Station Publication No. 54, 1943. 37 pages.
57. Koch, Alva E., "A Method of Soil Selection and Job Control for Rammed Earth Construction." Unpublished M.S. thesis, Civil Engineering Department, A. and M. College of Texas, College Station, Texas, 1947.
58. Lal, Manohar and Dhawan, B. L., "Use of Linseed Oil-Cake as a Stabilizer in Earth Construction," *Journal of the Indian Roads Congress,* Vol. 19, No. 2, p. 273, May, 1955.
59. Long, J. D. *Adobe Construction.* University of California, Agricultural Experiment Station Bulletin No. 472, November, 1946.
60. Long, J. D., "Adobe Structures for Earthquake Regions." *Agricultural Engineering,* Vol. 8, p. 173, July, 1927.
61. *Low Cost Housing.* Building Research Unit, Roorkee, U.P., India, B.R.U. Bulletin No. 1, September, 1949.
62. Lutz, J. F. *The Physiochemical Properties of Soils Affecting Soil Erosion.* Missouri Agricultural Experiment Station, Research Bulletin No. 212, 1934.
63. Lutz, J. F., "The Relation of Free Iron in the Soil to Aggregation," *Proceedings Soil Science Society of America,* Vol. 1, p. 43, 1936.
64. *Machine for Making Stabilized Earth or Sand-Cement Brick.* Ideas and Methods Exchange No. 10, Item F, International Housing Activities Staff, U. S. Housing and Home Finance Agency, Washington 25, D. C., July, 1953.
65. *Manual on Design for Low-Cost and Aided Self-Help Housing.* Ideas and Methods Exchange No. 37, International Housing Activities Staff, U. S. Housing and Home Finance Agency, Washington 25, D. C., January, 1957.
66. Martin, James P., "Microorganisms and Soil Aggregation: I. Origin and Nature of Some of the Aggregating Structures," *Soil Science,* Vol. 59, p. 163, 1945.
67. Martin, James P., "Microorganisms and Soil Aggregation: II. Influence of Bacterial Polysaccharides on Soil Structure," *Soil Science,* Vol. 61, p. 157, 1946.
68. Martin, J. P., and Waksman, S. A., "Influence of Microorganisms in Soil Aggregation and Erosion," *Soil Science,* Vol. 50, p. 29, 1940.
69. McCalla, T. M., "Influence of Biological Products on Soil Structure and Infiltration," *Proceedings Soil Science Society of America,* Vol. 7, p. 209, 1942.
70. McKesson, C. L., "Soil Stabilization with Emulsified Asphalt," *Proceedings* of the 15th Annual Meeting of the Highway Research Board, Washington, D. C., 1935.
71. Mehra, S. H., "Soil Stabilization in Tropical Areas for Mass Construction of Cheap Permanent Housing," *Proceedings* of the Third International Conference on Soil Mechanics and Foundation Engineering, Switzerland, Vol. I, p. 272, 1953.
72. Mehra, S. R., and Uppal, H. L., "Use of Stabilized Soil in Engineering Construction," *Journal of the Indian Roads Congress,* Vol. 14, p. 293, December, 1949, and Vol. 15, p. 184, August, 1950.
73. Mehra, S. R., and Uppal, H. L., "Use of Stabilized Soil in Engineering Construction, Section IV, 'Shrinkage of Compacted Soils'," *Journal of the Indian Roads Congress,* Vol. 15, p. 320, 1950-1951.
74. Merrill, Anthony F. *The Rammed Earth House.* New York: Harper and Brothers, 1947.
75. Middleton, G. F. *Build Your House of Earth.* London: Angus and Robertson, 1953.
76. Middleton, G. F., "Earth Wall Construction: Pise or Rammed Earth, Adobe or Puddled Earth, Stabilized Earth," Commonwealth Experimental Building Station, Sydney, 1952. 46 pages. (Australia Commonwealth Experimental Building Station Bulletin No. 5.) Supersedes duplicated document No. 28, references on p. 45.
77. Miller, T. A. H. *Adobe or Sun-Dried Brick for Farm Buildings.* Farmers Bulletin No. 1720, U. S. Department of Agriculture, Washington 25, D. C., 1934. 18 pages.
78. *Mud Brick Roofs.* Ideas and Methods Exchange No. 42, International Housing Activities Staff, U. S. Housing and Home Finance Agency, Washington 25, D. C., March, 1957.
79. Myers, H. E., "Physicochemical Reactions Between Organic and Inorganic Soil Colloids as Related to Aggregate Formation," *Soil Science,* Vol. 44, p. 331, 1937.
80. Narasimhan, J. S., and Krishnamurthy, K. V., "Stabilized Earth Bricks and Tiles for Buildings," Hyderabad Engineering Research Laboratory, India, Part II Soil Mechanics, Annual Report, 1952.
81. Narayana, S. K., "Materials and Methods of Building in Indian Villages," Bulletin of the Central Building Research Institute, Roorkee, Vol. I, No. 2, p. 16, October, 1953.
82. Neubauer, L. W. *Adobe Construction.* California Agricultural Experiment Station, Extension Service, Manual 19, 32 pages, undated.
83. "New Slant on Solidifying Mud," *Chemical Engineering,* p. 200, January, 1952.
84. Patty, Ralph L. *Clay Soil Unfavorable for Rammed Earth Walls.* South Dakota Agricultural Experiment Station, Bulletin No. 298, March, 1936. 23 pages.
85. Patty, Ralph L. *Paints and Plasters for Rammed Earth* Walls. South Dakota Agricultural Experiment Station, Bulletin No. 336, May, 1940. 39 pages.
86. Patty, Ralph L., "Soil Admixtures for Earth Walls," *Agricultural Engineering,* p. 291, September, 1942.
87. Patty, Ralph L., "Specifications for Rammed Earth Construction," *Agricultural Engineering,* p. 476, November, 1936.

88. Patty, Ralph L., and Minium, L. W. *Rammed Earth Walls for Farm Buildings.* South Dakota Agricultural Experiment Station Bulletin No. 277, April, 1933. 67 pages.
89. Peele, T. C., and Beale, O. W., "Influence of Microbial Activity Upon Aggregation and Erodibility of Lateritic Soils," *Proceedings Soil Science Society of America,* Vol. 5, p. 33, 1940.
90. "Pise Construction," *Journal of the Jamaica Agricultural Society,* Kingston, Jamaica, May, 1941.
91. "Pise Construction of Farm Buildings," *Queensland Agricultural Journal,* Brisbane, Australia, p. 67, July, 1931.
92. *Preliminary BRAB Bibliography of Housing and Building in Hot-Humid and Hot-Dry Climates.* National Research Council, Building Research Advisory Board (mimeographed), 32 pages, May, 1953.
93. "Proceedings of the Conference on Soil Stabilization," Massachusetts Institute of Technology, 1952.
94. *Proceedings, Housing and Building in Hot-Humid and Hot-Dry Climates.* National Research Council, Building Research Advisory Board, Conference Report No. 5, November 18 and 19, 1952. 177 pages.
95. "Proceedings of the Symposium on Scientific Principles and Their Applications to Tropical Building Design and Construction," National Institute of Science of India, New Delhi, date unknown.
96. *Rammed Earth,* Special Issue, Housing and Town and Country Planning Bulletin No. 4, United Nations, New York, p. 5, October, 1950. Articles:
    1. "Rammed Earth Technique in France," A. Marini.
    2. "Rammed Earth Technique in the United States," L. W. Neubauer.
    3. "Rammed Earth Technique in West Africa," A. E. S. Alcock.
    4. "Training Course for Building Rammed Earth Houses in Nyasaland," P. Williams.

    Glossary, Bibliography.
97. "Rammed Earth Building Improved in Australia," *American Builder,* p. 182, May, 1950.
98. "Rammed Earth Construction—Supplementary Information," Consumers Research, Inc., 1940.
99. "Rammed Earth for Farm Building Walls," *Agricultural Engineering,* January, 1934.
100. *Rammed Earth Walls.* South Dakota State College, Agricultural Experiment Station Circular 149, April, 1959.
101. *Rammed Earth Walls in House Construction, Experiences in Indonesia.* Ideas and Methods Exchange No. 15, Item J, International Housing Activities Staff, U. S. Housing and Home Finance Agency, Washington 25, D. C., May, 1954.
102. *Report on Egyptian Village Housing, Building Materials and Methods of Construction.* Cambridge, Mass.: Arthur D. Little, Inc., April, 1952.
103. *Resinous Water Repellents for Soils.* U. S. Waterways Experiment Station, Vicksburg, Mississippi, Technical Memorandum No. 217-1, May, 1946.
104. *Results on Experiments on Stabilizing Soil That Is to Be Used as a Building Material in Iran.* Ideas and Methods Exchange No. 51, International Housing Activities Staff, U. S. Housing and Home Finance Agency, p. 6, September, 1958.
105. Rosenak, S., "The Use of Soil-Cement for Low Cost Housing in the Tropics," *Civil Engineering and Public Works Review,* Vol. 52, October, 1957.
106. Scherecht, H. G., "Improve Physical Properties of Clays by Controlling pH Values," *Brick and Clay Record,* p. 18, March, 1938.
107. Schwalen, Harold C. *Effect of Soil Texture upon the Physical Characteristics of Adobe Brick.* University of Arizona, Technical Bulletin No. 58, 1935.
108. Sheets, Frank T., and Catton, Miles D., "Basic Principles of Soil-Cement Mixtures," *Engineering News-Record,* Vol. 19, June 23, 1938.
109. Sideri, D. I., "On the Formation of Structure in Soil: II. Synthesis of Aggregates; On the Bonds Uniting Clay with Sand and Clay with Humus," *Soil Science,* Vol. 42, p. 461, 1936.
110. *Soil and Soil Aggregate Stabilization, A Symposium.* Highway Research Board, Bulletin No. 108, 1955.
111. *Soil-Cement for Low-Cost House and Farm Building Construction in Rural Areas.* Portland Cement Association, Chicago, Ill., 1946.
112. *Soil-Cement Laboratory Handbook.* Portland Cement Association, Chicago, Ill., 1956.
113. "Soil Stabilization for Highways," Massachusetts Institute of Technology, Soil Stabilization Laboratory, July, 1954.
114. *Soil Stabilization in Tropical Areas for Mass Construction of Cheap Permanent Housing.* Ideas and Methods Exchange No. 9, Item J, International Housing Activities Staff, U. S. Housing and Home Finance Agency, Washington 25, D. C., May, 1953.
115. *Soil Tests for Stabilized Soil Construction.* Ideas and Methods Exchange No. 11, Item G, International Housing Activities Staff, U. S. Housing and Home Finance Agency, Washington 25, D. C., September, 1953.
116. Sparks, Morris M., "Adobe Brick Construction," U. S. Office of Technical Services, Washington 25, D. C., December, 1951. 13 pages.
117. "Stabilize with Chemicals?" *Chemical Engineering,* Vol. 59, p. 228, August, 1952.
118. "Stabilized Earth Wall Construction," Colonial Building Notes No. 8, United Kingdom Building Research Station, Watford, Herts, England, August, 1952. 12 pages.
119. "Stabilized Soil Bricks," *The British Constructional Engineer,* Vol 2, p. 40, August, 1951.
120. Stone, Ralph, "Soil-Cement for House Construction," *Civil Engineering,* Vol. 22, p. 1005, December, 1952.
121. *Surface Finishes of Stabilized Earth Walls.* Ideas and Methods Exchange No. 14, Item G, International Housing Activities Staff, U. S. Housing and Home Finance Agency, Washington 25, D. C., March, 1954.
122. "Symposium on Uses of Indigenous Materials for Low Cost Housing in Rureal Areas," *Journal of the Institution of Engineers* (India), Vol. 35, p. 5, September, 1954.
123. *Tapia Brick Buildings.* Ideas and Methods Exchange No. 2, Item I, International Housing Activities Staff, U. S. Housing and Home Finance Agency, Washington 25, D. C., December 8, 1952.
124. "Tentative Method of Freezing and Thawing Test of Compacted Soil-Cement Mixtures," ASTM Designation D 560-40T, 1940.
125. "Tentative Method of Test for Moisture Density Relations of Soil-Cement Mixtures," ASTM Designation D 558-40T, 1940.
126. "Tentative Method of Wetting and Drying Test of Compacted Soil-Cement Mixtures," ASTM Designation D 559-40T, 1940.
127. Uppal, H. L., and Bhatia, H. S., *Stabilization of Black Cotton Soil for Use of Road Construction.* The Indian Roads Congress, Road Research Bulletin No. 5, p. 105, December, 1958.
128. U. S. Department of Commerce, *Structural, Heat Transfer, and Water Permeability Properties of Five Earth Wall Constructions.* BMS78, National Bureau of Standards, Washington 25, D. C., October 1, 1941. 55 pages.
129. U. S. Department of Commerce, *Water Permeability of Masonry Walls.* BMS7, National Bureau of Standards, Washington 25, D. C., p. 12, 1938.
130. U. S. Housing and Home Finance Agency, *A Survey of Housing Research in the United States.* Washington 25, D. C., November, 1952. 723 pages.
131. Vasmani, N. K., "Effect of the Density of Compacted Brick on Its Crushing Strength," *University of Roorkee Research Journal,* Vol. 1, p. 86, November, 1958.
132. Vetter, F. K., "Low-Cost Self Built Housing." Unpublished M. of Arch. thesis, Library, A. & M. College of Texas, College Station, Texas, January, 1955.
133. Wallhouse, H., "Paint and Painting," Central African Council, Southern Rhodesia, Salisbury, Native Housing Technical Paper No. 6, June, 1949. 12 pages.
134. Webb, T. L., Cilliers, T. F., and Strutterheim, N., "The Properties of Compacted Soil and Soil-Cement Mixtures for Use in Building," National Building Research Institute, Union of South Africa, Pretoria, March, 1950. 62 pages.
135. Wiersma, J. L., "Hard Surfaced Floors for Farm Buildings," South Dakota Agricultural Experiment Station Bulletin No. 393, May, 1949. 28 pages.
136. Williams-Ellis, C., and Eastwick-Field, J. and E., "Building in Cob, Pise and Stabilized Earth," *Country Life, Ltd.,* London, 1947.
137. Winterkorn, H. F., "A Fundamental Approach to the Stabilization of Cohesive Soils," *Proceedings* of the Highway Research Board, Washington, D. C., p. 415, 1948.

138. Winterkorn, H. F., "Physico-Chemical Testing of Soils and Application of the Results in Practice," *Proceedings* of the 20th Annual Meeting of the Highway Research Board, Washington, D. C., p. 798, December, 1940.
139. Winterkorn, H. F., and Choudhury, A. N. Dutta, "Importance of Volume Relationships in Soil Stabilization," *Proceedings* of the 29th Annual Meeting of the Highway Research Board, Washington, D. C., p. 553, December, 1949.
140. Winterkorn, H. F., Fehrman, R. G., and McAlphin, G. W., "Waterproofing Cohesive Soil by Resinous Material," *Proceedings Soil Science Society of America,* Vol. 10, p. 458, 1945.

FILMS

141. "Hands to Houses," International Cooperation Administration, English, Approx. 15 minutes.
142. "Help Yourself to a House," International Cooperation Administration, No. 8.198, English, Approx. 25 minutes.
143. "Housing Adventure in Chile," International Cooperation Administration, No. 12.64, English, 28 minutes.
144. "It Can Be Done," International Cooperation Administration, No. 8.185, English, 28 minutes.
145. "Rumah Gatong Rojong," International Cooperation Administration, No. 8016.16, Indonesian (English summaries), Approx. 60 minutes.
146. "Showing the Way," International Cooperation Administration, No. 8.194, English, 12 minutes.

SECONDARY BIBLIOGRAPHY

147. Ackerman, P., "Old Adobe Comes Into Its Own—Finely Restored Home in Monterey, California," *House Beautiful,* p. 565, December, 1924.
148. Adams, J. W. *Adobe as a Building Material for the Plains.* Colorado Agricultural Experiment Station Bulletin No. 174, 1910.
149. "Adobe as a Historical Source," *Agricultural History,* Chicago, Ill., July, 1931.
150. *Adobe Brick for Farm Buildings.* Colorado Agricultural Experiment Station Bulletin No. 308, p. 1, 1926.
151. "Adobe Bricks Stabilized with Asphalt," *Engineering News-Record,* Vol. 140, p. 132, January 22, 1948.
152. "Adobe House Around a Patio in Los Altos, California—P. L. Bernhard Home," *American Home,* Vol. 24, p. 28, August, 1940.
153. "Adobe Houses," *Architect and Engineer,* Vol. 167, p. 12, October, 1946.
154. "Age-Strength Relationship for Rammed Earth," *Engineering News-Record,* Vol. 117, p. 44, July 9, 1936.
155. *Aided Self-Help in Housing Improvement.* Ideas and Methods Exchange No. 18, International Housing Activities Staff, U. S. Housing and Home Finance Agency, Washington 25, D. C., January, 1955.
156. Alcock, A. E. S., "Swishcrete," Colonial Building Notes No. 16, Building Research Station, Watford, Herts, England, September, 1953.
157. Alcock, A. E. S., and Richards, Helga M. *How to Plan Your Village.* New York: Longmans, Green and Co., 1953. 60 pages.
158. Aller, Paul and Doris, *Build Your Own Adobe.* Stanford, Calif.: Stanford University Press, 1946. 110 pages.
159. Ansley, C. F., "Restoring Our Devastated Regions," *Survey,* New York, p. 222, November 15, 1926.
160. "Arizona Adobe House with the Old Mesa Spirit—Home of B. J. D. Norfeldt, Santa Fe," *Arts and Decoration,* p. 72, July, 1927.
161. "Asphalt Stabilized Adobe Block Used with Post and Girder Frame," *Southwest Builder and Contractor,* p. 18, September 22, 1950.
162. "Attractive Pise Dwelling," *Queensland Agricultural Journal,* Brisbane, Australia, August, 1937.
163. Barket, R. L., "Hearths of Santa Fe," *House and Garden,* p. 86, February, 1927.
164. *Bitudobe Block Construction.* Baltimore, Md.: American Bituminous Company, n.d.
165. Brownfield, M., "Modernizing the Adobe," *Sunset,* p. 68, October, 1920.
166. Brugger, James R., "Built by Hand with Bitudobe," *American Home,* Vol. 43, p. 148, April, 1950.
167. Bryssine, G., "Typologic des Sols du Maroc," *Societe des Sciences Naturelles Et Physique du Maroc, Travanx de la Section de Pedologie,* 1954.
168. "Building with Mud," *Rural New Yorker,* p. 167, February 8, 1930.
169. Burris, Roy E., "An Inexpensive Method for Obtaining Heat Transfer Coefficients of Southwest Building Material." M.S. thesis, Library, University of New Mexico, February, 1948.
170. Carpenter, A. G. *How the World Is Housed.* New York: American Book Company, York, 1930.
171. Cassidy, L. L., "Ancient Adobe Restored—Winter Home of S. C. Hamilton, Santa Fe," *Sunset,* p. 54, September, 1928.
172. Cassidy, L. L., "No Garrets for these Artists—Cinco Pintores Colony, New Mexico," *Sunset,* p. 64, November, 1925.
173. Clough, Richard H. *A Qualitative Comparison of Rammed Earth and Sun-Dried Brick.* Albuquerque: University of New Mexico Press, 1950. (New Mexico University Publications in Engineering No. 4). 73 pages.
174. Conner, T., "Arts and Uses of Adobe," *House Beautiful,* p. 38, January, 1922.
175. Cook, Robert C., "Houses of Earth," *New Republic,* Vol. 109, p. 328, September 6, 1943.
176. Crane, Jacob L., "Homes of Earth," United Nations, New York, 1951 (?).
177. Crider, F. J., and Albert, D. W. *The Adobe Sweet Potato Storage House in Arizona.* Arizona Agricultural Experiment Station, Tucson, Arizona, n.d.
178. Cullimore, Clarence C. *Santa Barbara Adobes.* Santa Barbara, Calif.: Santa Barbara Book Publishing Company, 1948.
179. Dacy, H. G., "Rammed Earth Lowers House Cost," *Popular Mechanics,* Chicago, Ill., p. 838, November, 1924.
180. *Demonstration of Stabilized Mud Brick in Egyptian Village Housing.* Arthur D. Little, Inc., U. S. Department of State, Washington 25, D. C., September, 1953.
181. "Determining Colloids in Soil for Rammed Earth Construction," *Agricultural Engineering,* Vol. 16, p. 275, July, 1935.
182. "Dream in Adobe," *California Cintrograph,* July, 1947.
183. Duane, Frank J. *Experimental Features on Public Housing Projects.* U. S. Federal Public Housing Authority, Washington 25, D. C., 1945. 22 pages.
184. "Earth Stabilization with Bitumuls," *Building Standards Monthly,* Vol. 7, p. 4, January, 1938.
185. *Effect of Soil Texture Upon the Physical Characteristics of Adobe Bricks.* Arizona Agricultural Experiment Station Bulletin No. 58, p. 275, 1935.
186. Ellington, K. J., "More Mud Houses," *Scientific American,* New York, p. 174, March, 1925.
187. Emery, C., "Historic Hacienda Grande, San Diego," *Sunset,* p. 50, September, 1926.
188. "Experimental Results with Rammed Earth Construction," *Agricultural Engineering,* November, 1934.
189. "Experimental Soil-Cement Stabilization at Sheboygan, Michigan," Reprint Series No. 12, Department of Engineering Research, University of Michigan, Ann Arbor, Michigan, 1938. 32 pages.
190. Fincke, V., "I Wanted an Adobe House," *Arts and Decoration,* New York, p. 26, October, 1937.
191. Follis, George C. and Dobson, Louis E. *How to Build Adobe and Concrete Block Houses.* Culver City, Calif.: Murray and Gee, 1948.
192. Forbes, J. H., "Soil Cement Construction," *The Builder,* London, p. 359, September 14, 1951.
193. Gilman, E., "The Economical Builder—A Treatise on Tapia and Pise Walls," Washington, D. C., 1939.
194. Glenn, H. E., "Pressed Clay for Building Construction," Clemson Engineering Experiment Station Bulletin No. 5, October, 1951. 23 pages.
195. Gray, R. M., "A Mud Ranch House Designed by a California Engineer," *Agricultural Engineering,* p. 276, 1926.
196. Grigson, Geoffrey, "Puye in New Mexico," *The Listener,* London, p. 297, August 21, 1952.
197. Groban, W. E. *Adobe Architecture—Its Design and Construction.* U. S. Forest Service, Department of Agriculture, Washington 25, D. C., Publication No. M-5123, 1941.
198. "Gumption Story No. 6—This $1020 Home Took 'Git Up and Get'," *American Home,* Vol. 25, May, 1941.
199. Hansen, E. L., "Stabilized Mud for Building," *Engineering News-Record,* Vol. 126, p. 39, January 2, 1941.
200. Hardy, F., "Cohesion in Colloidal Soils," *Journal of Agricultural Science,* England, No. 4, p. 430, 1925.

201. Harrington, Mark R. *How to Build a California Adobe.* Los Angeles: W. Ritchie Press, 1948.
202. "He Built His House on Weekends," *House Beautiful,* March, 1946.
203. Hibben, Thomas, "Rammed Earth Construction," U. S. National Youth Administration, Technical Information Circular No. 16, Supplemental No. 1, 1940.
204. Hinchcliff, Keith H., "Leadership Training for Aided Self-Help Housing," International Cooperation Administration, 39 pages, undated.
205. Holman, R. L., "Dirt Cheap Houses," *Colliers,* p. 45, February 3, 1945.
206. Horn, Louis J., "Rammed Earth Houses," *Capper's Farmer,* November, 1951.
207. "House Adobe Built," *Travel,* June, 1945.
208. "House of Earth in New Mexico," *American Home,* Vol. 18, p. 32, November, 1937.
209. "Houses Built of Earth," *Architectural Record,* Vol. 80, p. 323, October 4, 1936.
210. "Houses Built of Rammed Earth," *Literary Digest,* Vol. 65, p. 21, April 24, 1920.
211. "Housing Center at Bogota Develops Soil-Cement Block Making Machine," *Building Science News* of the Building Research Institute, No. 22, September, 1957.
212. "How Germans Build Mud Houses," *Popular Science,* Vol. 151, p. 156, May, 1950.
213. "How to Sling Mud Constructively," *Better Homes and Gardens,* Vol. 19, p. 14, January, 1941.
214. Hubbell, Elbert, *Earth Brick Construction,* Education Division, Office of Indian Affairs, U. S. Department of the Interior, 1943.
215. Humphries, Lund, *Village Housing in the Tropics, with Special Reference to West Africa,* Great Britain, 134 pages. Reprinted 1953.
216. *Investigation of the Unconfined Compressive Strength of Soil-Cement Mixtures.* U. S. Waterways Experiment Station, Vicksburg, Mississippi, Technical Memorandum No. 187-1, February, 1942.
217. Jaggard, W. R., "Experimental Cottages," H. M. Stationery Office, London, England, 1921.
218. Jain, L. C., and Patwardhan, N. K., "Bricks from Soils of the Ganges Valley—I," *The Indian Builder,* January, 1956.
219. Kauten, Mat and Marie, "We'll Build It of Rammed Earth," *Woman's Home Companion,* p. 62, February, 1949.
220. Kern, M. D., "Restored Adobe in Santa Barbara," *American Home,* Vol. 15, p. 32, March, 1936.
221. Kirmser, E., "Why Not Dirt Houses," *American Mercury,* p. 86, July, 1947.
222. Knief, D., "Adobe Construction Branch Libraries—Kern County Free Library, Bakersfield, California," *Library Journal,* p. 100, February 1, 1939.
223. Larkin, Charlotte P., "Why I Built an Adobe Cottage," *Northland Gazette,* Kawakawa, Bay of Islands, N. Z., 51 pages, 1947.
224. Lee, A. B., "Houses of Earth," Box 171, Washington, D. C., 1937. 44 pages.
225. Legault, Adrian R., "Waterproofing of Adobe Tested to Extend Its Use into the Rainy Areas of the State," Colorado State College, Agricultural Experiment Station, *Farm Bulletin,* Vol. 5, No. 3, p. 13, July, 1943.
226. MacDowell, S., "Castles of Mud," *Sunset,* p. 23, February, 1926.
227. "Machine Builds Blocks Out of Soil-Cement," *Christian Science Monitor,* April 5, 1957.
228. "Mansion from Mud," *Popular Mechanics,* p. 107, November, 1947.
229. McDonald, Francis, *Terracrete, Building with Rammed Earth-Cement.* Obtainable only from author, Salinas, California. Date unknown.
230. McNown, W. C., "Soil-Cement Blocks for Walls at University Research Laboratory," *Engineering News-Record,* Vol. 127, p. 812, December 4, 1941.
231. Mears, Louis W., "The Sod House," *Journal of Geography,* p. 385, June, 1916.
232. Merrill, Anthony F., "Earth Blocks by Puddling," *American Home,* Vol. 38, p. 56, July, 1947.
233. "Methods of Construction and of Heat Insulation in Ukraine," *Journal Royal Institute of British Architects,* Vol. 52, p. 283, August, 1945.
234. Miller, T. A. H. *Report on Conditions of Rammed Earth Buildings Built 1820-1854, Sumpter, South Carolina.* U. S. Department of Agriculture, Bureau of Agricultural Engineering, Washington 25, D. C., 1926.
235. "Modern Pioneers in Arizona," *American Home,* Vol. 34, p. 41, Ocotber, 1945.
236. Mohan, D., "Consolidation and Strength Characteristics of Indian Black Cotton Soils," *Proceedings* of the Fourth International Conference on Soil Mechanics and Foundation Engineering, London, August, 1957.
237. Du Moulin, Rockwell King, *Rammed Earth Construction.* Washington, N. J.: Consumers Research, Inc., 1939.
238. "Mud House Comes Back—New Water-proofing Process Revives Ancient Building Art," *Popular Science,* p. 30, June, 1937.
239. "Mud Mansions—Detroit Co-op Builds Rammed Earth Homes," *Business Week,* p. 63, December 12, 1942.
240. Mumert, E. A., "They Build with Dirt," *Country Gentleman,* p. 27, September, 1941.
241. Murray, A. L., "Mrs. Ingleby's Adobe," *Sunset,* p. 64, November, 1922.
242. Murray, A. L., "Romance of the Adobe," *Overland,* p. 349, August, 1924.
243. Nelson, M. D., and Kauten, M., "Your Dream House Gets Down to Earth," *American Home,* Vol. 32, p. 36, July, 1944.
244. "New Adobe Houses," *Architect and Engineer,* Vol. 172, p. 19, January, 1948.
245. "New Methods, Old Type of Houses for Future, Rammed Earth Houses," *Science News-Letter,* p. 252, April 19, 1947.
246. "New Use of Mud," *Purdue Agriculturalist,* Vol. 35, p. 1, March, 1941.
247. "Out of the Good Earth Will Come Our Dream House—Rammed Earth Houses," *American Home,* Vol. 30, p. 24, September, 1943.
248. Patty, R. L., "Why Not Build Your Garden Walls of Earth," *American Home.* Vol. 20, p. 12, August, 1938.
249. *Physiological Objectives in Hot Weather Housing.* International Housing Activities Staff, U. S. Housing and Home Finance Agency, Washington 25, D. C., June, 1953. 79 pages.
250. Pierce, G. J., Jr. *A Six-Room House $2800 Complete.* Swampscott, Mass.: The Technical Press, n.d.
251. "Pise de Terre," *Agriculture and Livestock in India,* Calcutta, July, 1939.
252. "Pise de Terra," *Rhodesia Agricultural Journal,* Salisbury, September, 1925.
253. "Pneumatic Tamping in Rammed Earth Wall," *Agricultural Engineering,* August, 1929.
254. Popkin, C. A., "Adobe Has Its Place Too," *National Schools,* pp. 33 and 39, September, 1944.
255. Porter, J. W., "Houses of Mud," *Scientific American,* April, 1924.
256. "Prospective Coverings for Rammed Earth Walls," *Agricultural Engineering,* March, 1933.
257. "Puddled Earth and Rammed Earth Walls," *Agricultural Engineering,* August, 1939.
258. "Rammed Earth Offers Solution for Housing," *Engineering News-Record,* Vol. 129, p. 4, October 29, 1942.
259. "Rammed Earth, One of Man's Oldest Building Materials," *Architectural Forum,* p. 147, December, 1946.
260. "Rammed Soil for Buildings," *Science News-Letter,* p. 86, August 6, 1949.
261. Ramirez, George W. *Adobe.* Alhambra, California, 1946. 40 pages.
262. Rector, M. H., "Artist Turned Architect—Millard Sheets Creates Modern Rammed Earth Home at Claremont, California," *American Home,* Vol. 32, p. 38, June, 1944.
263. "Regulations Respecting Earth Structures," Great Britain Department of Science and Industrial Research, *Building Science Abstracts,* Vol. 15, p. 173, November, 1942, and Vol. 16, p. 42, March, 1943.
264. *Report of Committee on Lime—Soil Stabilization.* Ameri-Road Builders' Association, Washington, D. C., Technical Bulletin No. 147, 1948.
265. Richards, Helga M. *How to Plan Your Market.* New York: Longmans, Green and Company, 1957.
266. Robinson, S., "Houses Dirt Cheap—Rammed Earth Building," *Rotarian,* Vol. 55, p. 24, August, 1939.
267. Rutz, L. C., "House That Ben Built in Mesilla Park, New Mexico," *American Home,* Vol. 23, p. 95, May, 1940.
268. Smmaha, Melhem T., "Bituminous Adobe Bricks," Beirut, Lebanon: Bourge-Hammond, n.d.

269. Sangh, Hindustani Talmi, "Report on the Construction of Some Sample Rammed Earth Building Blocks Which Is the First Phase of a Continuing Experiment," Sponsored by the Ministry of Education of the Government of Bihar, India, n.d.
270. Smith, G. E. Kidder, "Report from Morocco," *Architectural Forum,* p. 64, June, 1950.
271. *Soil Bituminous Roads.* Current Road Problems No. 12, Highway Research Board, National Research Council, Washington 25, D. C., September, 1946.
272. "Soil Stabilization—Symposium at Institution of Highway Engineers," *The Surveyor and Municipal and County Engineer,* London, p. 789, December 8, 1951.
273. "Solid Ground for Progress," *Chemical Week,* Vol. 70, p. 35, May 10, 1952.
274 "A Story from the Southwest," *Rural New Yorker,* p. 260, April 9, 1938.
275. "Tropical Building Design and Construction Symposium," *Science,* Vol. 117, p. 582, May 29, 1953.
276. U. S. Department of Agriculture. *Experiments in Rammed Earth Construction.* Farm Security Administration (Succeeded by the Farmers' Home Administration), Washington 25, D. C., November, 1938. Reprinted, FSA Publication 59, June, 1942.
277. U. S. Department of Agriculture, "Houses of Rammed Earth Construction," Resettlement Administration, Washington, D. C., 4 pages, n.d.
278. U. S. Department of Agriculture, "Statement on Condition of Rammed Earth Houses," Farmers' Home Administration, Washington 25, D. C., 1940.
279. "The Use of Adobe in Construction," *American Builder,* Vol. 73, p. 169, April, 1951.
280. Verrill, A. H., "Adobe House," *Country Life,* Vernon, B. C., Vol. 52, p. 71, October, 1927.
281. Verrill, A. H., "Built of Mud," *Scientific American,* Vol. 143, p. 110, August, 1930.
282. Vivian, C. H., "Houses Built of Rammed Earth," *Compressed Air Magazine,* Vol. 32, p. 1945, March, 1927.
283. Von Blon, J. L., "Mansions of Mud," *Scientific American,* p. 218, February 28, 1920.
284. Wadsworth, B. M., "Home Integrated with Creative Arts and Crafts—C. and P. Bolsius Home, Tucson, Arizona," *School Arts,* p. 229, March, 1944.
285. Welch, R. F., "Adobe Renaissance," *Christian Science Monitor Magazine,* p. 4, July 24, 1948.
286. "West Coast Houses Do Get Down to Earth," *Construction Methods,* Vol. 29, p. 110, July, 1947.
287. Whitehorne, E. E., "Adobe House Electrical," *House Beautiful,* p. 60, January, 1922.
288. "Why Not Rammed Earth?" *Rotarian,* August, 1946.
289. Williams, M. O., "Mud House Won a National Prize," *Sunset,* p. 50, October, 1928.
290. Winterkorn, H. F., "Fundamental Similarities Between Electro-Osmotic and Thermo-Osmotic Phenomena," *Proceedings* of the 27th Annual Meeting of the Highway Research Board, Washington, D. C., p. 443, December, 1947.
291. Winterkorn, H. F., "New Way to Make Low-Cost Drives, Walks, Terraces, Barbeques—Stabilized Soil," *The Countryman's Guide.* Noroton, Conn.: The Country Bookstore, n.d.
292. Winterkorn, H. F., "Nouvelles Recherches en Matiere de Stabilization des Sols," *Annales* de l'Institut Technique du Batiment et des Travaux Publics, Paris, p. 933, September, 1952.
293. Woods, K. B., "Lime as an Admixture for Bases and Subgrades." Paper presented at the 31st Annual Convention of the National Lime Association, Washington, D. C., May, 1949.
294. Wright, Frank Lloyd, "El Paso, Texas—Patio Type Adobe Dwelling in Desert Sand," *Architectural Forum,* p. 97, January, 1948.