1938

Rammed Earth Walls for Farm Building (Revised April 1938)

Agricultural Experiment Station, South Dakota State College

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BULLETIN 277

REVISED APRIL 1938

RAMMED EARTH WALLS FOR FARM BUILDINGS

DEPARTMENT OF AGRICULTURAL ENGINEERING
AGRICULTURAL EXPERIMENT STATION
SOUTH DAKOTA STATE COLLEGE
BROOKINGS, SOUTH DAKOTA

A List of Reference Books and Literature on Pise' Construction

NOTE: Rather than to quote extensively, earlier work that has been done on pisé de terre construction, the authors wish to list the following references dealing with the subject. Single copies of the bulletins listed can usually be obtained free of charge while the books can be obtained at a very reasonable cost.

Farmers' Bulletin No. 1500, "Rammed Earth Walls For Buildings", United States Department of Agriculture.

Bulletin No. 472, California Agricultural Experiment Station, Berkeley, California. A book, "Cottage Building in Cob, Pisé, Chalk and Clay," by Clough Williams-Ellis. Distributed by Charles Scribners Sons, New York City.

A booklet, "Lower Cost Buildings", by E. W. Coffin and H. B. Humphrey, The Publicity Corporation, 22 Thames St., New York City.

A book, "Modern Pisé Buildings," by Karl J. Ellington, Port Angeles, Wash.

Second Edition

This is the second edition of Experiment Station Bulletin 277-1933, slightly revised and containing a supplement of results and progress up to 1938 that was not reported in Experiment Station Bulletin 298 published in 1936 and entitled "The Relation of Colloids in Soil to Its Favorable Use in Pisé or Rammed Earth Walls."

Explanation of Cover Cut

The South Dakota Poultry House Built With Rammed Earth Walls, At The South Dakota State College, Brookings.

The earth walls of the house are warm and wind proof. The house is warm in winter and cool in hot summer weather. The walls remained free from frost until the outside temperature fell to 18 degrees below zero. Two years after these walls were painted the paint began to fail in spots. The paint was all removed and the building was stuccoed in 1934. The stucco is standing perfectly.

Table of Contents

Rammed Earth Walls for Farm Buildings

By Ralph L. Patty and L. W. Minium[1]

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INTRODUCTION

Rammed earth walls are made by ramming ordinary moist earth into forms. The walls are rammed in place directly upon the building foundation and in sections. The forms are similar to those used for concrete construction except that they must be much stronger and heavier. The ramming may be done either by hand or by mechanical power.

The purpose of this experimental study of "pisé" construction was to secure definite and reliable information with which we could answer the many inquiries concerning it that were coming to the State College Experiment station. The wide range of soil types over the state of South Dakota made it impossible to make reliable recommendations as to its use for this construction without a careful and detailed study of South Dakota soils, and of soils in general, for this purpose. This is a progress report.

Earth construction for building walls is not a new idea. In fact, it is ages old. Buildings were built of earth centuries ago in Europe, and while the methods used differed widely, some of this construction was of rammed earth. It is claimed that pisé construction was used by the early Romans and was introduced into France by them. The following paragraph is taken from Farmers' Bulletin No. 1500 by M. C. Betts and T. A. H. Miller.

"Pisé de terre (pronounced pee-zay duh taire), the French for rammed earth, is an ancient type of construction. The writings of Pliny state that watch towers of this material constructed by Hannibal were in use 250 years after completion. It was introduced into France by the Romans and later adopted in England."

Buildings of these walls have been used in the United States also to a limited extent. According to California Experiment Station Bulletin No. 472 by J. D. Long some of the settlers of our early colonies built of this material. One two-story rammed earth residence now in use in Washington, D. C., is said to have been erected in 1773, and a modern residence was built of this material in Washington within the past few years by Dr. H. B. Humphrey.

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1 Mr. Minium has been with the Soil Conservation Service since 1934. The authors particularly wish to acknowledge the cooperation of Professor H. M. Crothers, Dean of Engineering, and of Associate Professor J. G. Hutton and Leo Puhr of the Agronomy Department, Professor W. E. Poley and Prof. W. C. Tully of the Poultry Husbandry Department, and Dr. K. W. Franke of the Chemistry Experiment Station, South Dakota State College. They also wish to acknowledge the assistance in this study of senior students, Leslie W. Johnson, Ward C. Hendon, Delbert Taute and other students who have given the most careful assistance in the work of ramming test pieces and test walls and in helping prepare the soils, and the kindness of Mr. D. E. Wiant in reading and correcting the copy.

Other Types of Earth Walls.—There are several types of earth wall construction besides the pisé or rammed earth walls with which this study deals. Adobe walls, as the term is generally understood and defined, are made of a wet plastic mixture of earth or mud. Adobe walls should not be confused with rammed earth as they are quite different, the adobe being mud-like while the pisé walls are rammed dirt. The most common adobe construction is from blocks. The mud is tamped and molded into large bricks usually 18 inches long by 12 inches wide by 4 inches thick. These are often reinforced with straw, and after they are molded they are set out to dry. When they are properly cured they are laid into a wall in the same way as concrete blocks. Adobe or mud walls are also made by packing the wet mud into forms, making a mon-

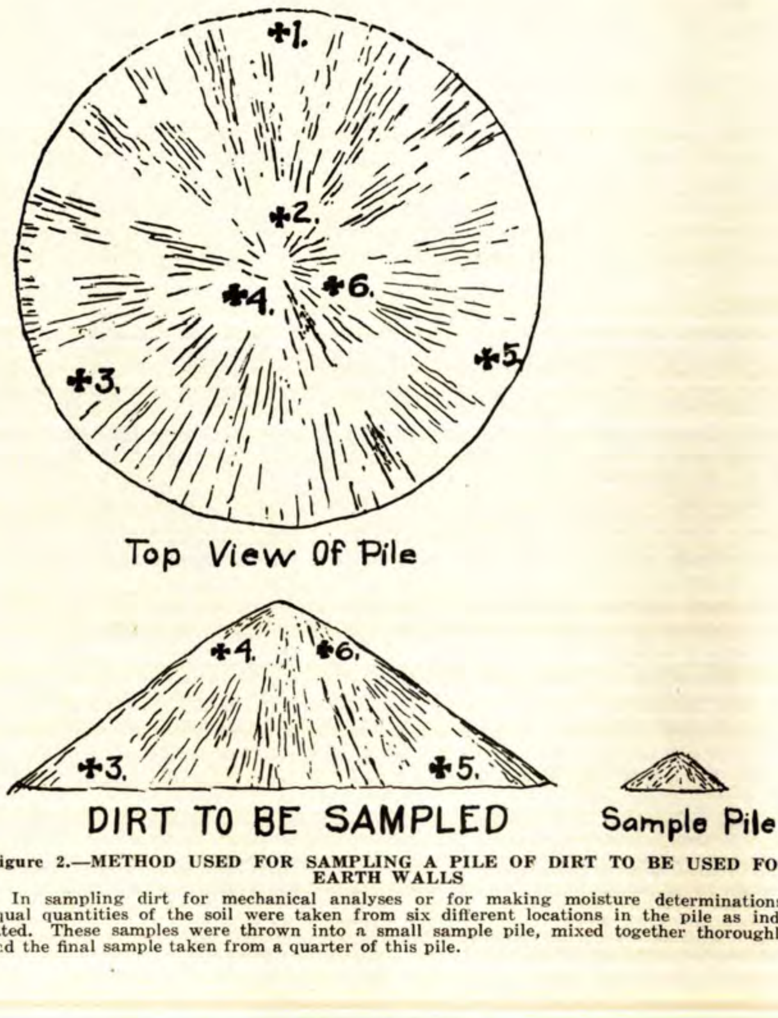


Figure 2.—METHOD USED FOR SAMPLING A PILE OF DIRT TO BE USED FOR EARTH WALLS

In sampling dirt for mechanical analyses or for making moisture determinations, equal quantities of the soil were taken from six different locations in the pile as indicated. These samples were thrown into a small sample pile, mixed together thoroughly and the final sample taken from a quarter of this pile.

olithic wall. In most of these walls straw or other binder material has been generally used. There are other variations in the use of earth for wall construction that are of less importance and perhaps less practical. In the South Western states the adobe brick are used extensively. Mexican laborers are generally more or less experienced in making these brick and the work can be done when farm work is slack. The authors believe the rammed earth wall may be better adapted to the North Central section of the United States because of inexperience in making adobe brick and because of a great deal of experience in building of concrete, and the use of forms in making monolithic walls. The monolithic wall is also entirely resistant to the infiltration of cold air in winter. The rammed earth wall is a "once over, all over" method. It saves two or three handlings of the dirt and also saves the mortar for laying the bricks. In a warm climate of even temperature mud is fairly satisfactory for the mortar used to lay the bricks, but for more rigid climates where loosening of the mortar joints would result in a cold wall, the monolithic or one-piece wall should be preferable. The heavy forms used for rammed earth construction are not built all the way around the foundation of the building as for pouring concrete. One or two sections of form only, are required. The wall is rammed a section at a time, and after one section is rammed the form is then moved ahead and another section is rammed.

The dirt used for rammed earth walls is not wet and in no way approaches mud. Generally the dirt that is excavated for the basement of a house will be too moist for making the best walls. Dirt that will make a mud ball is too wet. It should have only enough moisture in it to hold together when it is pressed in the hand. Clean dirt of this moisture content is easy to handle and makes a wall that will not check badly, one that is smooth and resistant to shock, a good insulator and a surface that does not bake.

Practicability and Insulating Quality of Rammed Earth Walls.—One very important reason for this experimental study is the need for insulated walls for housing livestock and poultry in climates subject to cold weather in the winter season. Moisture and frost accumulate on the inside surface of cold side walls in such a climate. The greatest damage from this frost accumulation comes when the weather moderates. The thawing of the frost from the walls makes the building damp and creates a condition that is unhealthful for livestock and particularly bad for poultry. Rammed earth walls are excellent insulating material and up to the present stage of this study have proved very satisfactory in the control of moisture and frost. A poultry house was built with rammed earth walls and straw loft on the college poultry farm[2] for the purpose of comparing frost deposit and inside temperatures with several other houses.

During the first part of the 1932 winter season the weather was abnormally cold and the temperature dropped to 18 degrees below zero. A thorough inspection of the inside walls during this period revealed no trace of frost on the inside walls of the rammed earth house, while in the other houses the frost deposit varied from light to heavy. Later in the season the temperature dropped to 30 degrees below zero and the frost deposit on the rammed earth walls was almost as heavy as on the walls of other houses of frame and tile construction with average insu-

2 See page 58.

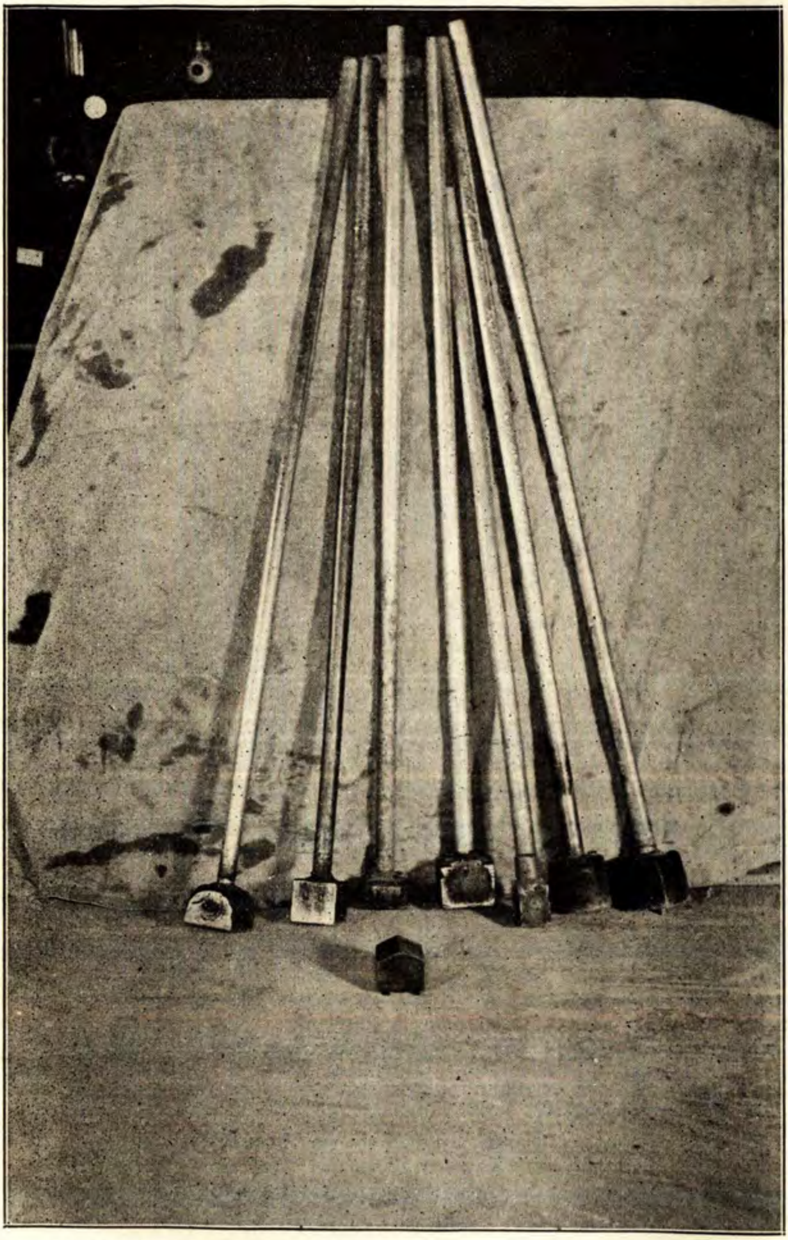


Figure 3.—A COLLECTION OF HAND RAMMERS USED IN BUILDING RAMMED EARTH WALLS.

The square, flat faced rammer, weighing from 15 to 18 pounds, is preferred by the workmen. The shaft is made from one inch galvanized pipe. The rammer head shown in the foreground has a beveled face, the sides making an angle of 30 degrees with the horizontal. Workmen did not like to use this rammer and test pieces made with it were not as strong in compression as those made from the flat faced rammer.*

*See Table No. 6.

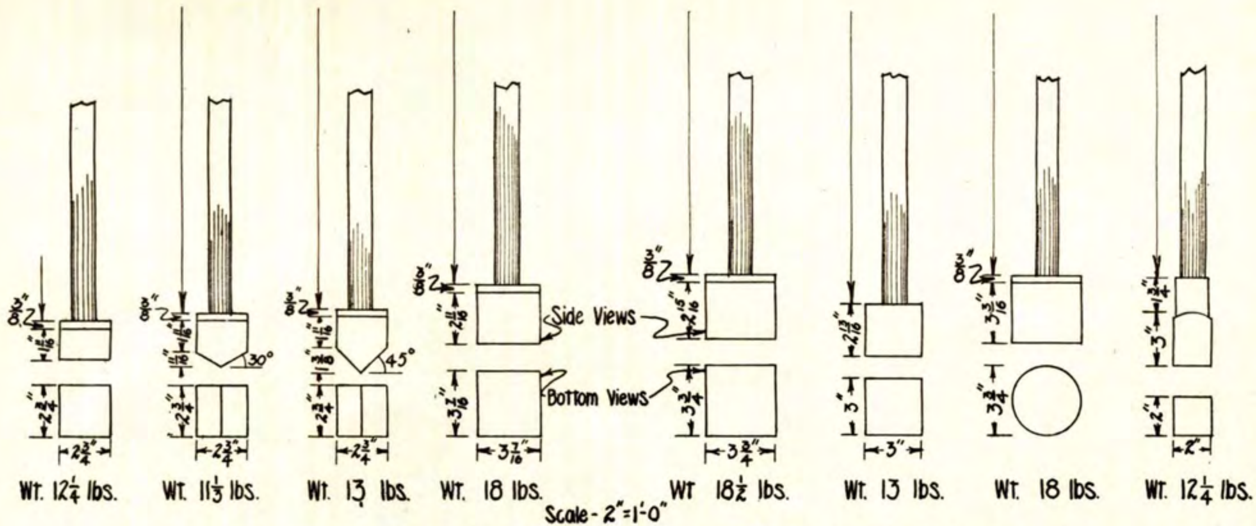


Figure 4.—A DRAWING OF VARIOUS KINDS OF HAND RAMMERS THAT HAVE BEEN USED IN THE STUDY.

All of the rammer heads were of cast iron or steel and the shafts were made from one inch galvanized pipe. The exact dimensions of the rammer heads are given.

lation. All of these houses had straw lofts except one and in this house the frost condition was more than twice as bad as in the rammed earth house. The frost did not appear to make the inside of the "rammed earth" house as damp as the others. There was a noticeable difference. The rammed earth wall was only 12 inches thick.

It was a desire on the part of the experiment station to find an inexpensive and satisfactory wall for the farm poultry house, that made this study of economic importance. A cooperative study of this poultry house is being carried on at the present time by the Agricultural Engineering department and the Poultry Husbandry department. The project will include a study of temperature control, moisture control, and egg production in this type of house.

Rammed earth construction lends itself well to construction of simple buildings with comparatively low sidewalls and few wall openings. A building such as average sized farm poultry houses can be built above the foundation in 10 days to two weeks time by an experienced crew of three men. If the labor must all be hired there will be little, if any, saving in the cost of the walls over those built from lumber or building tile. The advantage of rammed earth construction must be in utilizing labor for which little or no cash must be paid and in securing an exceedingly warm and dry sidewall for the poultry house. For more elaborate buildings of more than one story the work is more tedious, forms and frames for openings require more time and if the labor is hired the cost is apt to be fully as great if not greater for rammed earth construction than for other materials. However, this study has verified former claims made by investigators and enthusiasts for rammed earth construction that most excellent homes and buildings can be built of earth if desired. Although under normal conditions the cost of elaborate buildings of rammed earth may be as high, the walls, if kept well painted or stuccoed, should last indefinitely and be exceedingly well insulated.

One author[3] recommends that before starting on an elaborate building of rammed earth it would be well first to build a small simple structure and thereby become familiar with the use of the forms and the characteristics of the soil. Such a building might be a small smoke house, vegetable storage cellar, garage, or a farm poultry house.

Mechanical rammers may be used in the constructing of rammed earth walls. Their use will cut down the labor hours for this work but the cost of a complete compressed air outfit for ramming will cost several hundred dollars at the present price. The California experiment station[3] reports that with the mechanical rammer a construction speed of 7 cubic feet per man hour was secured. With hand ramming a speed of 2 cubic feet per man hour would be about as much as could be expected of an experienced crew of men. In building the walls of the poultry house at the South Dakota experiment station the speed averaged one and one-half cubic feet per man hour. Student labor was used entirely for this work, however, and the work was not only done intermittently but new men had to be broken in on the work.

3 J. D. Long—California Experiment Station Bulletin No. 472.

Description of This Study in Brief

The purpose of these studies was to learn the characteristics of soils favorable to rammed earth construction, to determine the optimum clay and sand ratio, and the optimum moisture content for both strength and weathering resistance in rammed earth walls. Further studies were made on protective coverings, on the effect of adding fiber to the dirt, on rammers and the proper ramming of dirt into the forms, on reinforcing for wall openings and corners, and on the best practices in building walls of this material. Finally, the study of the cost and economy of rammed earth walls and their relative insulating value in the control of frost deposit when used for housing livestock.

The strength tests in compression were made to determine the relative value of certain soil characteristics or building practices, and not because of its questionable strength for farm building walls. Walls made from soils showing the lowest strength would be amply strong to carry the compression load in walls. Although there is a tendency for planes of cleavage to develop between the layers of earth as they are rammed in test blocks and beams, they do not seem to be a factor of importance in walls. Various attempts have been made to overcome this difficulty in the test pieces and some results have shown improvement but nothing entirely satisfactory. Work is still being done on this problem. Samples of soils from all parts of South Dakota were analyzed and tested both for strength and for resistance to weathering. These soils were taken from 18 counties of the state and covering the extreme territories.[4]

Test Blocks and Beams.—All test blocks were cubical in shape and were 9 by 9 by approximately 9 inches. They were about as heavy as can be conveniently handled, weighing from 45 to 60 pounds when first made, depending upon the amount of sand in the dirt. They were rammed in forms as shown in Fig. 9, and with hand rammers. They were handled on board trays 12 inches square.

The test beams were made for the reinforcing study and were 36 by 12 by approximately 7¾ inches in depth. They weighed from 250 to 260 pounds and were handled on slat trays approximately 10 inches by 48 inches.

Testing the Soil for Moisture.—The moisture tests of soils were made in duplicate. Measures of the soil were taken from six different points in the pile and placed in a small sample pile which was then mixed and quartered. From this dirt duplicate samples of 400 to 500 grams each were placed in soil pans. These were weighed and placed in an electric dispatch oven where they dried out to constant weight at a temperature of approximately 220 degrees F. The samples were then reweighed and the loss of moisture figured. The per cent of moisture was then determined by dividing the loss of moisture by the net weight of the wet sample of soil. The average of the duplicate figures was used for the true moisture percentage.

Testing the Blocks for Strength in Compression.—All test blocks that were tested for strength in compression were stored in the research laboratory in a temperature around 70 degrees F. until the moisture content was reduced to almost a constant figure. This moisture content averaged below three per cent at the time they were broken. In order to

4 See Weathering Wall Study.

determine the moisture contained in the blocks at any time, the blocks were weighed immediately after they were made and when the moisture content of the soil was known. By reweighing a block at a later date the moisture content could be figured from the loss in the weight of the block. This was done in the following manner: The weight of the new block multiplied by the moisture content of the soil from which it was made in per cent, gave the weight of water in the block in pounds.

After the block had dried out it was reweighed and the loss of weight in pounds (which was necessarily the weight of the moisture lost) was subtracted from the pounds of water originally in the block. This gave the weight of the moisture, in pounds, that was left in the block, and dividing this figure by the weight of the dry block gave the moisture content of the dry block in per cent. The blocks were handled at all times on a small board tray 12 inches square and of known weight, so that no loss of weight could result in handling. The blocks were made in the form of cubes 9x9x9 inches. It was not always possible to get the depth of the blocks exactly nine inches and when this variation was sufficiently great, slight correction was made for it. The blocks were crushed in a Riehle testing machine.[5]

Since the bottoms of the blocks were perfectly square and level they were seated upon a one-fourth inch fiber pad for the test. A sand cushion leveling the top of the block and covered with a second fiber pad was used on the top of the block. The strength figures are surprisingly uniform for these test pieces of such material. Similar test blocks of a series

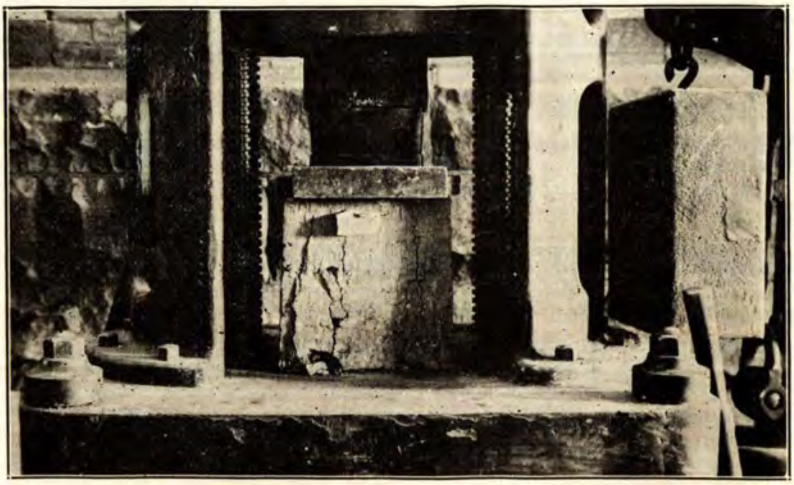


Figure 5—TESTING THE RAMMED EARTH BLOCKS FOR COMPRESSIVE STRENGTH

The blocks were crushed in a Riehle testing machine when their strength in compression was desired. This block shows a typical failure, indicating a sound block or one without any special flaw or weakness. It failed under a load (ultimate load) of 36,000 pounds or 18 tons which is about an average strength for South Dakota soils. The dimensions of the block are 9x9x9 inches. 400 of these test pieces have been broken so far in the study.

5 See Fig. 5.

seldom varied more than three or four per cent and an average of three or four blocks has usually proved a reliable and satisfactory figure. The manner of testing the test beams is described under the paragraph on "reinforcing in rammed earth construction" and a picture of the test is shown in Fig. 6.

Soil Used for Standard in Tests.—Three standard soils were used for making test pieces when a standard base soil was needed for comparing the effect of certain conditions or practices. They are designated as experimental soil No. 1, Experimental Soil No. 2, and Experimental Soil No. 3. Experimental soil No. 1 is a black clay soil obtained in a valley one-half mile north of the experiment station. It is composed of 89.6 per cent silt and clay and only 10.4 per cent of sand, most of which is fine. Experimental soil No. 2 is a yellow clay loam soil found in the subsoil under all of the higher ground upon which the college campus is located. It averages only 62.5 per cent clay and silt and contains 37.5 per cent of total sand ranging in size from particles that are just retained upon a very fine screen of 200 mesh to the lineal inch, up to one inch in size. Experimental soil No. 3 is a darker yellow sandy clay loam soil found in a certain local area near the campanile on the State College campus. This soil is very high in total sand and gravel content, containing only 25.2 per cent of clay and silt with a total sand or aggregate content of 74.8 per cent. The aggregate is very well graduated in size varying all the way from the 200 mesh size up to two inches. This soil has characteristics all its own. It is by far the most favorable soil for rammed earth construction, from the standpoint of weather resistance, that has as yet been found in the State.

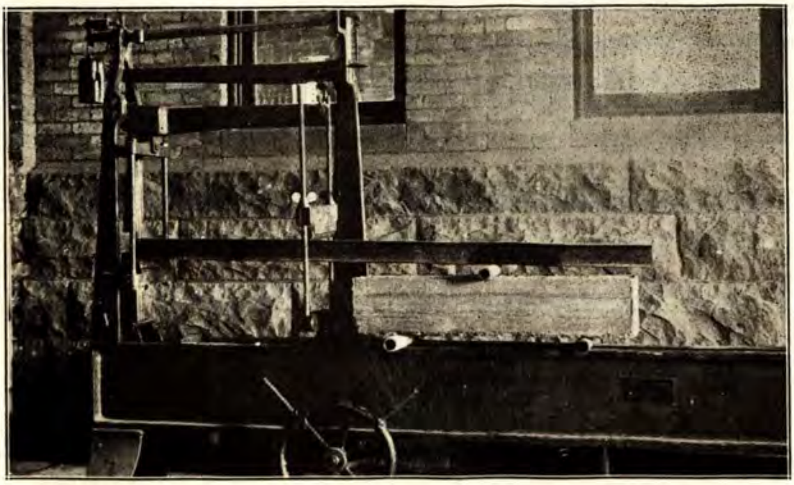
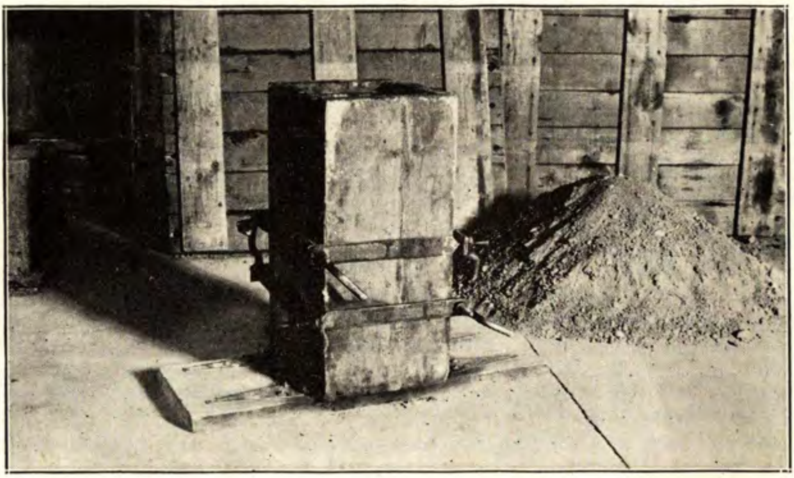


Figure 6.—TESTING RAMMED EARTH BEAMS USED IN THE REINFORCING STUDY.
The beams were 36 inches long, 12 inches wide and 7¾ inches high. The reinforcing materials were placed one and one-half inches from the bottom of the beam. The span used in the test was 24 inches and force applied at the top, midway between the two contact points. The Olsen testing machine was used.



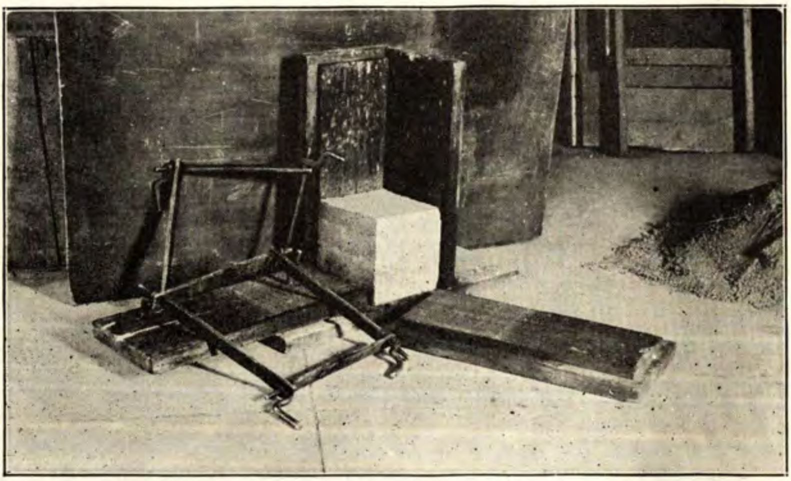


Figure 7.—FORM USED FOR MAKING RAMMED EARTH TEST PIECES.

A. The form set up ready for ramming a 9x9x9 inch test piece. Notice that the heavy strap hinges had to be bolted down, as heavy screws would not hold. The bottom plank extends out for enough so the operator can stand on it while tamping.

B. Form partly taken down showing finished block ready to be removed. This form is practically identical to the one used by J. D. Long at the California Experiment Station and shown in Farmers' Bulletin No. 1500, United States Department of Agriculture. The block is 9x9x9 inches in dimension.

Mechanical Analysis of Soil Samples.—In analyzing the soils for this study no attempt has as yet been made to separate or study the silt and clay materials.[6] The analyses have been made in the following manner: Duplicate samples of approximately 500 gms. have been thoroughly dried in the electric dispatch oven until reduced to constant weight. They were then weighed and passed through the following sized screens in order: three-fourths inch, one-half inch, and one-fourth inch. The sample was then screened through the one-eighth inch, the 100 mesh (100 mesh to the lineal inch), and the 200-mesh screens under a stream of water. The sand retained on these screens was then dried and each size was carefully weighed. For simplicity the total aggregate, from the finest particles that were retained on the 200-mesh screen up to the largest pebbles will often be referred to in the tables and in this bulletin as "sand." All soil particles that passed through the 200-mesh screen is considered silt and clay.

Table 1.—Mechanical Analysis of Three Base Used in Experimental Blocks and Beams

Soil	Color	Number of Samples Averaged	Total Silt and Clay Per cent	Sand			Gravel		Total Aggregate Per Cent
				200 to 100 Mesh Screen	100 to ⅛ in. Mesh Screen	⅛ in. to ¼ in. Mesh Screen	½ in. to ¼ in. Mesh Screen	½ in. Screen and Above	
Experimental Soil No. 1	Black	4	89.641	4.514	5.76	.085			10.36
Experimental Soil No. 2	L. Yellow	4	62.44	8.799	24.354	1.918	1.662	.826	37.56
Experimental Soil No. 3	D. Yellow	4	25.18	4.690	41.870	9.390	7.200	11.670	74.82

6 Analyses of these soils have since been made by means of the hydrometer test. Silt has been separated from the clay and total clay colloids have been determined for all soils. These tests have been reported in Exp. Sta. Bul. No. 298 which is a technical bulletin and as such would be of interest for technical use only. Total sand in soils will average about 11% higher with the hydrometer test than with the above sieve tests.

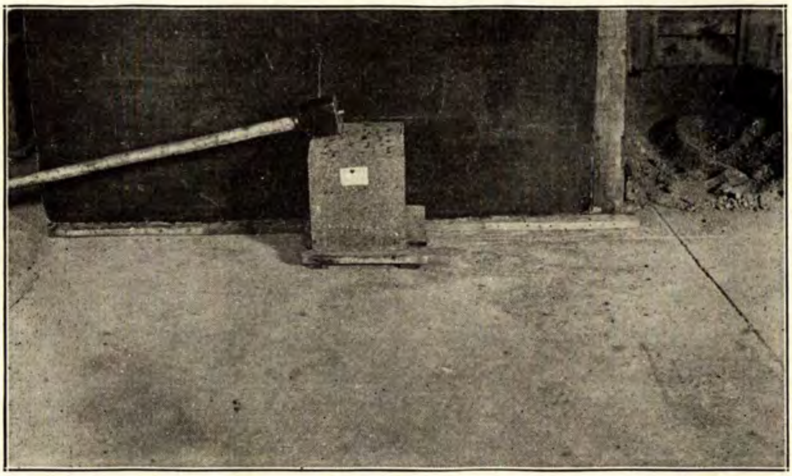


Figure 8.—A NUB-RAMMER USED IN AN EXPERIMENTAL ATTEMPT TO SECURE A BETTER BOND BETWEEN THE LAYERS OF EARTH IN A RAMMED EARTH WALL.

Although there is undoubtedly a weakness in the plane betwen layers of the rammed earth in pisé construction, and especially when flat faced rammers are used, it does not seem to be a serious factor. However, some study has been made to overcome this weakness and this rammer was made for a trial. The resulting tests on its use are now pending. The nub is in the shape of a cone frustrum. It is five-eighths inches long and tapers from a diameter of five-eighths at the butt to three-eighths at the tip. The holes left in the layer by this nub can be seen in the top of the test-block.

Figure 9.—FORM USED FOR MAKING RAMMED EARTH WEATHERING TEST WALLS.

The tremendous side thrust exerted by the dirt while being rammed may be realized by noting the 2x4 inch stiffeners on this form. Originally only three stiffeners on each side were used but they were not strong enough, making it necessary to use four on each side.

Relation of Sand Content, Moisture, and Shrinkage In Soils for Rammed Earth Work

The first study made was for the purpose of finding out the effect of sand content and moisture, in the soil used, upon the rammed earth wall. Thirty-nine test blocks were made for this study with the idea of observing them and later of testing them for compressive strength. Five different amounts of sand were used in this series of blocks and the moisture was varied from high to low in three graduated amounts within the bonding range. The blocks were closely observed as they dried out and the shrinkage was measured. After the blocks had dried to constant weight they were tested for compressive strength in a Riehle testing machine and the results are given in Table No. 2.

Moisture and Sand.—This study disclosed several relationships between the amount of moisture in the soil and the properties of the rammed earth. It was found that the optimum moisture for ramming varied in inverse proportion to the amount of sand in the soil, as the sand in the soil was increased the required moisture decreased. This is due to the fact that soil that is made up of small particles (silt and clay) has a much greater surface area for moisture than soil containing coarser particles of sand and gravel with the silt and clay. A sandy soil containing only seven or eight per cent moisture would be wet while a clay soil with this per cent of moisture would be altogether too dry to ram. It would require 16 to 18 per cent of moisture to bring this soil up to the uptimum moisture for ramming. Bank run sand and gravel alone will be quite wet when containing only three or four per cent of moisture.

Moisture and Strength.—The amount of moisture in the soil has a decided effect upon the strength of rammed earth in compression. When too dry all soils seem to lose strength markedly, and in most cases soils that are too wet show a low strength. This is particularly evident with sandier soils and it is probable that this may be due to the larger amount of space left in the block after the moisture has evaporated. Such a block seems much less dense and the present status of the study, purely from the strength standpoint, indicates that in rammed earth construction density may be as important a factor for strength as in concrete.

Sand and Strength.—The results have not as yet shown definitely that the strength of rammed earth varies in inverse proportion to the amount of sand in the soil, but there is no doubt of this proportion for higher amounts of sand. It is highly probable that in general, soils containing 30 per cent or more of sand decrease in strength in inverse ratio and possibly this ratio might carry all the way through if the weakening effects of cracking and checking in the blocks containing little sand could be avoided.

Moisture and Shrinkage.—The study leaves no doubt about the relationship of moisture and shrinkage. Regardless of the soil and its characteristics the amount of shrinkage varies in direct ratio with the amount of moisture in the soil at the time it was rammed, i.e., provided the moisture is sufficient to bond the dirt well. This fact is also shown in Table No. 2. Although the shrinkage may not be very great in the sandier soil it will increase with the increased moisture. With the less sandy soils shrinkage is not only a very important factor in rammed earth construction but may be a limiting factor. In these soils a comparatively large amount of moisture is needed to make the dirt wet enough to bond and this means a high shrinkage and large shrinkage cracks and checks.[7] These checks appear to reduce the resistance of the soil to weathering, causing them to crumble away when the surface is exposed to the weather. This may not be in direct proportion but apparently it generally is.

Sand and Shrinkage.—Sand in the soil reduces shrinkage of rammed earth in direct proportion by reducing the amount of moisture that is required in the soil at the time it is rammed. Soils containing 50 per cent or more of sand do not shrink enough to cause cracking or checking of the wall to any extent. In this connection it is interesting to note that in a long wall there will be some shrinkage however, and that the amount of shrinkage that will be expected can be figured. In order to figure it, it is first necessary to determine the shrinkage coefficient of a certain soil by testing. For instance, if it is found that a test block of a certain soil shrinks .5 per cent, then for every 100 inches in the length of the wall there will be a shrinkage of one-half inch. This may be largely taken up or absorbed in many hair-like cracks or there may be a larger one or two, or the joint between the sections of the wall as they were rammed may pull apart slightly to take up this shrinkage. The shrinkage of the blocks has been difficult to measure as accurately as desired. For the first part of the study it was measured in the various dimensions of the block with an engineer's steel rule. Since the forms in which the blocks are rammed have a slight amount of give to them it has been difficult to devise a satisfactory apparatus for making these measurements. At present a metal tape is being used to measure the perimeter of the blocks at three grad-

Figure 10.—A PISE WALL FROM SOIL IN WHICH THERE WAS NOT ENOUGH SAND.
The checks and cracks shown in this wall section were caused by shrinkage forces and are typical of heavy clay soils in which there is very little sand. This soil contained only 11 per cent of sand by weight, and the 89 per cent was silt and clay. Unfinished experimental work indicates that this kind of dirt can be used satisfactorily if it is plastered after 30 days of drying weather.

7 See Fig. 10.

Table 2.—Relation of Moisture, Strength and Shrinkage in Rammed Earth Test Blocks****

Per Cent Moisture Content in Soil	Sand 0 to 5 Per Cent		Sand 10 to 20 Per Cent		Sand 25 to 35 Per Cent		Sand 42 to 53 Per Cent		Sand 55 and Above	
	Per Cent Shrinkage	Strength Compression lbs. Per Sq. In.	Per Cent Shrinkage	Strength Compression lbs. Per Sq. In.	Per Cent Shrinkage	Strength Compresion lbs. Per Sq. In.	Per Cent Shrinkage	Strength Compresion lbs. Per Sq. In.	Per Cent Shrinkage	Strength Compresion lbs. Per Sq. In.
6									.14	147.7
7							.18	226.1	.—	191.5
8								141.4	.00	198.5
9					.80	464.1	.91	404.1	.68	292.3
10			1.33	374.3	.66	626.0	.662	609.5	.00	246.0
11	.42	273.	1.72	439.0	.66	531.6	.50	509.0	.15	205.8
12	.40	877.5*	1.85	605.	1.35	523.5	1.19	381.0	.33	441.0*
13	1.66	400.	1.51	493.	1.30	353.0				
14	2.43	576.5			.86	352.5				
15	2.8	385.								
16			2.01	522.	2.04	511.0*				
17			3.16	344.5						
18	2.23	692.0*	1.00	270.						

* Figures that fall out of line for the strength curve.

** Later findings show that some of the variations in strength in this table were due to a difference in the age of the test piece when broken.

NOTE.—As the sand content increases the shrinkage decreases. As the sand content increases above 35 per cent the strength decreases. As the moisture increases the shrinkage increases.

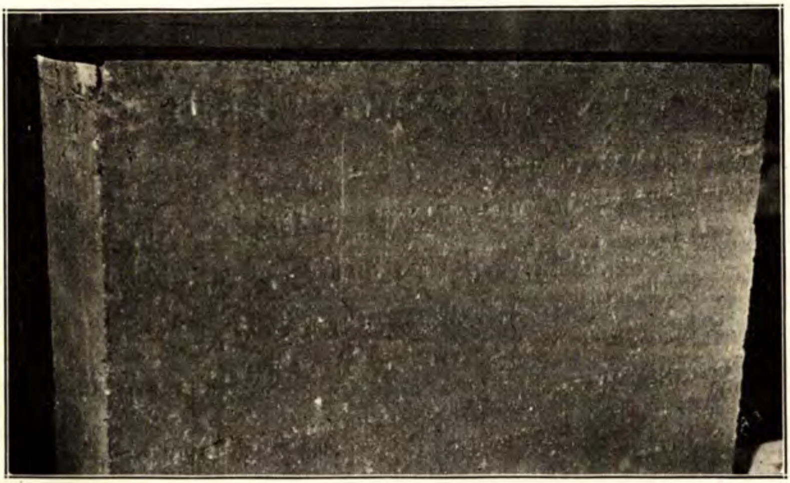


Figure 11.—AN EXCELLENT SOIL FOR RAMMED EARTH WALLS.

This wall was made from dirt that is almost perfect for rammed earth construction. It is made from Experimental Soil No. 3* and had stood for nearly two years when the picture was taken. This is the south side of the wall, however, and the north side is somewhat roughened from driving rains from the north. This dirt contained 74.8 per cent of sand by weight, and the shrinkage for it was almost negligible.**

* See Table No. 1.

** After 8 years of weathering no appreciable change can be seen in this wall since the above picture was taken.

uated distances in the depth of the block, and the shrinkage figured from it. The fact that there is a possibility of slight error in measuring the shrinkage may account for a slight variation from the regular curve in the table. However, the general trend of the shrinkage is shown clearly to decrease as the sand in the soil increases.

For practical purposes the results of the study of this relationship for sand, moisture, and shrinkage show that the optimum moisture should be used for best strength and weathering. Although this optimum moisture varies with the amount of sand in the soil it is easy to determine it by practical tests described in a following paragraph, and with a little ex-

Table 3.—The Relation of Sand Content to Unit Weight

Soil	Experimental Soil No. 1. Sand Content 10.36%	Experimental Soil No. 2 Sand Content 37.56%	Experimental Soil No. 3 Sand Content 74.82%
Unit Weight	℔ per cu. ft. 119.4.	℔ per cu. ft. 128.38	℔ per cu. ft. 138.87

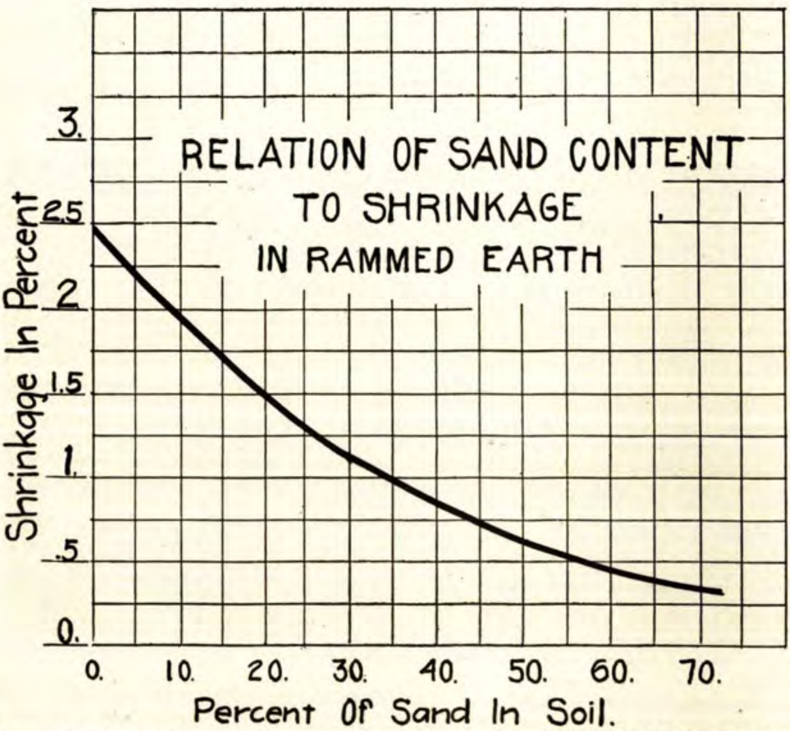


Figure 12.—AS THE SAND INCREASES IN THE SOIL USED FOR RAMMED EARTH THE SHRINKAGE IN THE WALL DECREASES.

This curve is developed from the average shrinkage of test pieces used in compiling Table No. 2.

perience a mere feeling of the dirt is sufficient. Sand in the soil reduces the compressive strength of the soil somewhat, but it is very valuable in reducing shrinkage and in increasing the resistance to weathering as further discussed in the paragraph following. In Table No. 2, p. 21, the results that are shown not only include the 39 blocks made especially for this study, but includes some additional blocks that are of widely different character, thus adding considerable value to the results shown. Practically every strength figure and the corresponding shrinkage figure for a certain moisture and within the range of sand, are averages of several different blocks.

The Unit Weight of Soils in Rammed Earth

As stated previously, the work that has been done so far indicates that the strength in rammed earth may vary directly with the density for a soil containing large amounts of sand. As in concrete, a well graduated aggregate containing all the different sizes of aggregate up to the size of an egg increases the density of the wall directly, and probably the strength in the same proportion. This would only be true of soils having equal amounts of sand in them, for the heaviest, densest soils will not have the greatest strength because they will be sandy and the very sandy soils have less strength than those containing more clay. In this study the unit weights of the soil have been recorded, but since no definite relationship for it has turned up to make it an important factor in the study, they have not been used. The unit weight has been shown in only one table, Table No. 3.

By unit weight is meant the weight of the soil per cubic foot, and in this study it was usually figured for all test pieces after they were thoroughly dried out. However, the figures shown for unit weight in the table below

Figure 13.—AN EXPERIMENTAL WALL OF HEAVY CLAY OR "GUMBO" SOIL.

A. This wall section shows extreme checking and cracking of an earth wall due to a very low sand content of the soil used.

B. At the right is the surface of the same wall several months later. The cracks settle together to quite an extent after the moisture leaves, but the wall crumbles away.

are for test pieces that were just made and containing all of the original moisture. It is interesting to note the relationship of unit weight and the sand content in the soil. The three base soils used in all our experimental work were chosen because they represented three widely different soils. In total sand content they vary almost in a direct proportion and their unit weight varies accordingly. The figures shown in table No. 3 are averaged from 12 blocks of each soil.

Optimum Moisture in Soil for Weather Resistance

One or two experiences in the study suggested that a higher moisture content in the soil than is needed for maximum strength might be desirable for resisting weather. This fact is quite satisfactorily disproved by the following trial. A composite sample of an average soil containing 35.7 per cent total sand was selected and used for making four rammed earth walls. These walls were built exactly alike except for moisture content. They were given the same location in the yard and were made by the same workmen, care being used to ram the same. The first wall was rammed very dry, having only 6.59 per cent moisture in the soil. The second wall was rammed with 9.10 per cent moisture, which is the optimum moisture in this soil for strength in compression. The third wall was slightly too wet, having 11.58 per cent moisture. The fourth wall was made very wet—in fact, just as wet as it was possible to ram it. The moisture content was 14.01 per cent. The walls have been standing for 18 months.

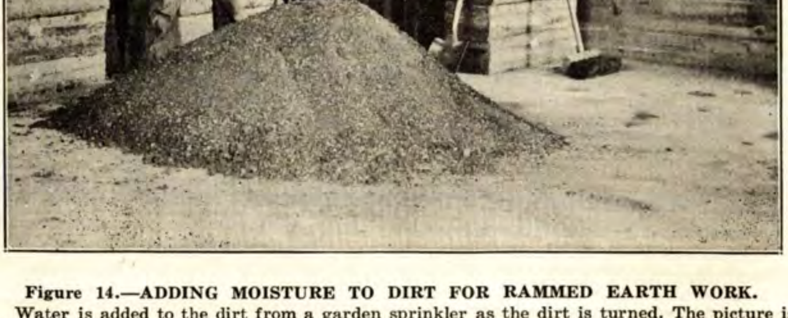


Figure 14.—ADDING MOISTURE TO DIRT FOR RAMMED EARTH WORK.
Water is added to the dirt from a garden sprinkler as the dirt is turned. The picture is taken inside the research laboratory of the department of agricultural engineering, South Dakota Agricultural Experiment Station.

Results: Wall No. 1[8] made from the dry soil, and wall No. 4 made from the extremely wet soil are showing poorest. Of the two walls of intermediate moisture, wall No. 2, having 9.10 per cent moisture is showing slightly superior to wall No. 3, having 11.58 per cent moisture. The optimum moisture for strength for this same soil is approximately 9.10 per cent.

Kind of Soil Best Adapted to Rammed Earth Construction

Contrary to the prevailing opinion, tight clay soils and soils often referred to as "gumbo" are the poorest kind for rammed earth construction. The study has shown that such soils are unfit for use unless they are protected with paint or other suitable protective covering. Linseed oil and ordinary outside house paint is the only covering that has been tried on this particular kind of soil as yet. Present indications are that if the "gumbo" walls are painted within five or six days after the forms are removed they may stand satisfactorily.[9]

The most satisfactory soil for rammed earth construction will have a considerable amout of sand in it, ranging from 30 per cent to 80 per cent with the optimum amount around 75 per cent. The best test wall in the yard is made from soil having 74.8 per cent of sand in it.[10] Some soils with 20 per cent of sand are standing quite satisfactorily. The study has proved quite definitely that the sand or aggregate when as high as 70 per cent is used will have a somewhat greater strength in walls if it is well graduated from the fine particles up to the large pebbles, with a majority of the finer aggregate. When there is such a graduation of aggregate the finest particles fit in between the larger sizes and the larger sizes fit into the spaces of the still larger pebbles, and so on. The soil mentioned above, having 74.8 per cent of sand in it, contained sand that was exceedingly well graduated. It is the experimental soil No. 3 and the mechanical analysis of it is given in Table No. 1. This soil has the highest unit weight of any soil that has yet been found, averaging 138.87 pounds per cubic foot after being rammed.

Few soils containing less than 20 per cent of sand were found satisfactory for rammed earth construction, and 35 to 50 per cent was much better. Many agricultural soils will be found to fall in the group containing 20 to 50 per cent of sand and will be found satisfactory. Sand can be added to a dirt slightly deficient in sand with very little trouble. In fact, if the sand is convenient, it can be added on the mixing board with scarcely any additional labor, and it would be advisable, especially if the wall is to be left uncovered. Very few soils with less than 50 per cent of sand will stand as a bare wall and 70 to 75 per cent is apt to be more weather resistant. Soils of medium quality can be used quite satifactorily when stuccoed.

8 Wall No. 1 later proved to be definitely the poorest wall of all and crumbled badly. Wall No. 3 which was too moist proved to be far better than wall No. 1 which was too dry. There is a tendency for workmen to ram the walls too dry, and these dry spots will crumble badly. The moisture should be kept up to a point where there is a slight tendency for the dirt to stick to the rammer.

9 Later study shows definitely that paint will not be satisfactory on heavy clay soils. Soils containing more than 30 per cent of clay are entirely unsatisfactory for rammed earth walls.

10 Sand as used in this report includes all the hard aggregrate that will not pass through the 200 mesh screen or will not float off when the dirt is washed in a pan. Some of the pebbles may be almost as large as the fist, while the finest grains will just be retained on the 200 mesh screen.

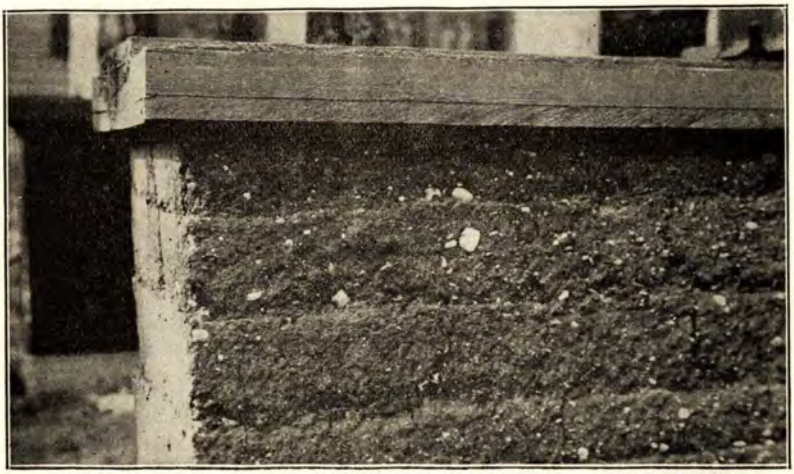


Figure 15.—THE EFFECT OF DRIVING RAINS UPON BARE RAMMED EARTH WALLS.

This wall section is made from a medium favorable dirt, and yet one driving rain in near freezing weather in November 1930 roughened the surface as shown. The picture was taken nine months after the wall was built.

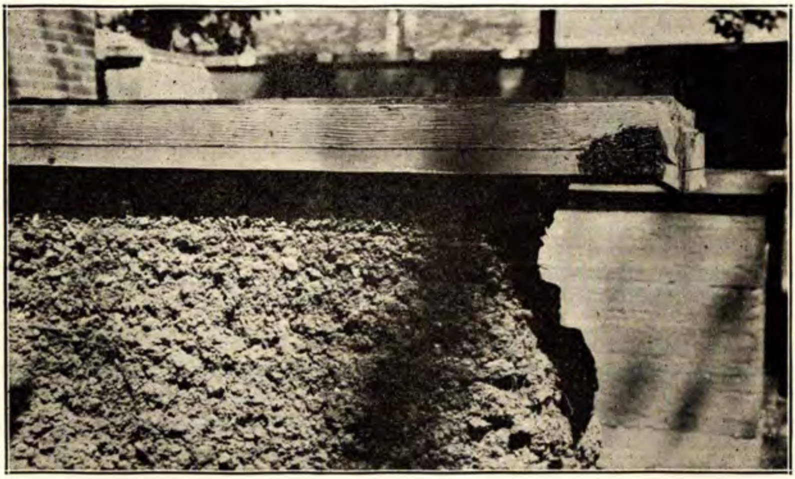


Figure 16.—AN OUTLAW SOIL.

This soil has characteristics all its own that are not revealed by a mechanical analysis. Perhaps a chemical analysis will show why it behaves in this way. The picture was taken exactly one year after the wall was made. It was torn down and rebuilt and the result was the same.*

*** The answer to this question has been found. The soil contains 55.2 per cent total clay colloids. It is next to the heaviest clay soil in the yard although it did not appear to be so heavy. Any soil with 40 per cent or more of clay colloids is unfit to use.**

A Simple Test of Soil for Rammed Earth Work

In spite of the fact that there is a wide range of soils that can be used successfully for rammed earth work when stuccoed, a good soil will require a little less care in ramming and, still more important, will stand longer in case the covering is neglected after the building becomes old. As stated above, such a soil will have between 50 per cent and 80 per cent of sand in its structure. A simple test can be made to determine whether a soil falls in the class of good soils or not. Take an average sample of the soil in a flat pan and dry it in a hot oven for three or four hours. A wash basin will answer perfectly for this purpose. The amount of soil should be more than a quart. Next, pulverize the soil fairly well so it will not have many lumps in it. Pebbles of all sizes should be left in the sample. Fill a quart cup with the dry dirt and settle it down so the cup is entirely full. Place the dirt in a wash basin or other flat pan and cover with water, then stir with the hand and pour off the dirty water. Fill the pan with clean water and repeat this operation until all the fine silt and clay particles are floated off. It will only take a few minutes until all the dirt is gone and the water will remain clear. What is left in the pan will be clean sand and some of it will be very fine. Dry the sand and measure it in a measuring cup. If there is a full cup of sand there is approximately 30 per cent of sand by weight in the soil, and it will be fairly good for rammed earth work. If there is more than a cup of sand and not more than three cupfuls it should be an excellent soil for the work.

Exceptions to the Sand Silt-Clay Ratio.—The above ratio of sand to silt-clay indicates just how satisfactory a soil will be for pisé work in practically all cases. Exceptions were found to this, however, in the study. In no case was a soil with a sand content of 30 per cent or more found to be a poor soil, but two soils with a low sand content were found to be quite good. One of these having only 20 per cent of sand has continued to show good weathering resistance while in the case of the other having 19 per cent sand stood well for nearly two years, after which it began failing rather rapidly. This last soil, a Spearfish loam from the Black Hills area of South Dakota and bright red in color was distinctly different and did not shrink or check in the same manner as other soils of low sand content. Both of these soils, however, were used in corrected walls to which sand was added up to 45 per cent and their resistance to weathering is obviously improved. It is very evident that these soils are high in silt content. Only two soils were found that seem to be impossible to use. One of these contained 17.3 per cent sand. Its colloidal nature seems to render it totally unfit for rammed earth work. The test wall from this soil failed twice and was rerammed.[11] The second time it was rebuilt it was painted and again it failed within a year. The other soil was of Pierre clay, commonly called "gumbo." It was a better soil than the one above but the surface gradually scaled and crumbled away. This wall was also rebuilt and painted, and it also failed completely. It was then stuccoed in the same way as the other walls and again it failed.

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11 See Fig. No. 16.

Effect of Reramming Dirt in Pise' Construction

Dirt that has once been rammed into a structure can be broken up and used again if desired. A trial was made of this by ramming a test block of experimental soil No. 1. The block was tested for strength in the compression machine, being tested to destruction. After it was broken the pieces were ground up on the concrete floor of the testing laboratory by means of the rammers and the dirt was used again in making another block within a few hours. The second block was tested in the same machine and its strength was slightly higher than that of the original block, due, no doubt to the anxiety of the operator to do a careful job of ramming. Only a slight amount of moisture was lost from the first block due to the ramming process.

Effect of Freezing Weather upon Rammed Earth Construction Work

Contruction work can be carried on in any reasonable weather as long as the dirt is not frozen and the temperature does not fall too much below freezing. However, it is advisable to avoid freezing weather when possible. During the fall of 1930 a large wall section was being built at intermittent intervals throughout the month of November and up until Christmas time. Although the weather was generally mild, the temperature fell somewhat below freezing on several occasions, and with no evident injury to the wall. In January of 1933 a small weathering wall was rammed with the temperature at 18 degress F. and zero temperatures followed within a few days. The temperature of the soil used in this wall was above 60 degrees F. when the wall was rammed because the dirt had been kept inside.

It is yet too early to predict that the wall is unharmed but no serious injury has as yet become evident. Three days after the wall was completed the temperature rose to well above freezing and the wall was given a coat of paint. Observation for two or three years may be necessary to determine for certain the effect on this wall.[12] In one trial there seems to be evidence of injury from freezing. A small weathering wall rammed late in the fall of 1932 was caught by an extremely cold temperature that lasted for several days. This wall appears to have been injured by freezing as two large sections of it seem to have been moved out of line with the rest of the surface by the action of frost.

Care of the Dirt for Rammed Earth Work

Care of the dirt for rammed earth work is of greatest importance. The work can be done in almost any kind of weather if the dirt is kept dry. Dirt that is too dry can easily be corrected by sprinkling the pile and turning it carefully on the mixing board. It is better to do this the day before it is used, as the moisture will help to distribute itself in the pile during the night. A temporary shed as shown in Fig. 23 is almost a necessity if no other cover is handy. Sheeting lumber to be used for the roof of the building can be used in making this shelter. Another way to add moisture to dirt that has become only slightly too dry under the shelter is to pile a load or two outside where it will get the rains. A few

12 In 1938 this wall is standing in excellent condition. The dirt used was very favorable.

shovels of this damp dirt with each batch shoveled on to the mixing board will secure the correct moisture. In adding moisture it will always save time if a certain number of shovelfuls are used for each batch and a measured amount of water is added each time. In this way there is no guess work and it is important to have the moisture content reasonably uniform.

Screening the Dirt for Rammed Earth Work.—It is not necessary to screen the dirt that is to be rammed unless there is some special reason for it. If there were large pieces of tree roots in the dirt it would be desirable to screen them out, or if the dirt contained hard dry clods it would be necessary to screen them out. A stone as large as a hen's egg would do no damage in the wall if there were not too many of them. In the work here at the experiment station practically no material that has been rammed into walls has been screened. All of the experimental dirt used in making test blocks and test beams in the laboratory is screened.

Effect of Depth of Block Upon the Strength in Compression

Since it was found practically impossible to make the test blocks exactly the same depth or height, it is necessary to make corrections for the blocks when this difference is appreciable. In order to determine the exact ratio of the depth of the test piece to its compressive strength so as to determine the correction coefficient, a series of blocks was made varying the depth of the blocks in graduated amounts. Since the standard test blocks are rammed in four layers, each being a trifle over two inches in thickness, one series of blocks was made only one layer in

Figure 17.—A SMALL RAMMED EARTH BUILDING USED FOR EXPERIMENTAL PURPOSES.

One writer suggests that it would be a good plan for one who is planning to build rammed earth walls to build a small building first in order to become accustomed to the soil and to the handling of the forms. The authors do not believe this is necessary but a small building such as a smoke house or garage would be a good one to build if it is desired to follow this suggestion.

depth averaging 2.24 inches. A second series of blocks was made two layers in depth averaging 4.4 inches. A third series of three layers averaged 6.675 inches, while a fourth series of the standard four layers averaged 8.9 inches in depth. The strength varied inversely as the depth of the test piece. The four thinnest blocks were too strong for the 100,000 lb. testing machine. The blocks having a depth of 4.4 inches averaged 662 lbs. per square inch, those having a depth of 6.67 inches averaged 334, while those having a depth of 8.9 inches averaged only 191.5 lbs. per square inch. Experimental soil No. 3 was used. It is a very sandy soil and is not a strong soil comparatively, but in this series the blocks were all low in strength even for this soil. The figures are summarized in Table No. 4 below. The correction coefficient as figured from this test is 5.3 lbs. per square inch for each tenth of an inch the test piece may vary above, or below, nine inches in depth.

Table 4.—Effect of Depth of Test Block upon the Strength in Compression

No. of Blocks of Each Tested	Depth of Blocks (Av.) in Inches	Av. Ultimate Breaking Load in Pounds	Compressive Strength in Lbs. Per Sq. Inch	Age When Broken (Days)	Moisture Content When Made	Moisture Content When Broken	Weight of Blocks in Lbs. (Average)
4	2.24	*	1,234.+	35	7.92%	0.33%	15
4	4.40	51,625	662.	35	7.92%	0.45%	30
4	6.67	27,050	334.	35	7.92%	0.85%	45
4	8.90	15,515	191.5	35	7.92%	1.32%	62

* These blocks stood more than 100,000 pounds, which was the limit of the testing machine used.

Resistance of Rammed Earth Walls to Weathering

In determining the resistance of a soil to weather action small test walls were built of each different soil to be tested. These walls are 12 inches thick, 36 inches long and approximately 30 inches high. They are covered on top with a flat roof that projects 1½ inches on all sides. This type of roof was found unsatisfactory as the water in time of heavy rain is apt to flow back underneath this overhang and down the face of the bare wall. When this happens grave damage is done as the flowing water cuts the earth surface like a knife. Quarter round was used to prevent the water from flowing underneath, but with a heavy wind there was still some injury from this source. The covers were then edged with sheet steel strips with the lower edge of the strips projecting an inch below the plank and this trouble was eliminated. It was not intended to protect the walls from direct rain action, but a peaked roof with the same projection would be more practical and more satisfactory for this purpose. The walls were built on concrete foundations, with exactly the same width as the walls, extending 12 inches below and 6 inches above grade. When the walls were built some of the foundations were covered with water-proofing materials and others were left untreated for the purpose of comparison. Ninety walls have been built up to this time in this weathering series. Corrected walls have been built to see if an addition of sand, or of clay, or an adjustment in moisture content would improve the original wall. For each wall made from a different type of soil a corrected wall has been built in the testing yard.

This study is in its early stages yet and such conclusions as have been drawn from it are brought out in the discussions on "kinds of soil" and on "optimum moisture content." One striking fact that has been learned is that the north side of the bare test walls weather much faster than the south side. This is due not only to injury from driving rains that prevail from the northwest, but the natural crumbling and weathering is decidedly more rapid on the north side.[13] This condition is exactly opposite to the finding in the case of most of the protective coverings being tested on the wall panels. In the case of the coverings a slight advantage was indicated in favor of the covering on the north exposure, and this condition also agrees with the findings at the Iowa Experiment Station in regard to the weathering of prepared roll roofing.

As reported in Iowa Engineering Experiment Station Bulletin No. 49 by Giese, Barre, and Davidson, the roofing on the south exposure weathered more rapidly than on the north. One condition that has not been satisfactorily explained as yet is that the small weathering walls apparently weather more rapidly than the large walls.

The study to date indicates that protective coverings for rammed earth walls are highly desirable if not absolutely necessary in this region, for any except the most favorable walls. The best walls may be soon roughened on the north side from driving rains, and most of the

Figure 18.—A CORNER OF THE RAMMED EARTH EXPERIMENTAL YARD AT THE SOUTH DAKOTA EXPERIMENT STATION AT BROOKINGS, SOUTH DAKOTA.

This shows the type of small weathering wall used in the study. The roofs or covers as shown were not satisfactory as heavy rains caused the water to run back under the roof projection and down the face of the wall in some instances. This cut the wall like a knife. A peaked roof would be better than the type shown. Ninety of these experimental walls walls have been built up to the present time.

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13 New walls weather more rapidly. After one or two years the walls made from favorable soils become more resistant and are affected very little by the hard driving rains.

medium soils are beginning to crumble slightly within three years' time. A covering of some effective material such as a covering of cement plaster would not only protect the wall surface against ordinary weathering, but would protect it against flowing water which might strike in an emergency, or in the case of an old building that had been neglected.

For this same reason it is highly desirable that the tops of walls be protected under and around the plate with paint or perhaps better, with a thick layer of rich cement mortar. This mortar would also serve to level up the plate on the top of the wall. In the case of plaster or stucco it is best to wait until all the shrinkage cracks and checks have appeared before plastering, in which case the cracks will be filled and will reinforce the bond of the plaster to the wall.

Protective Coverings for Pise' Walls

Mention was made several times of the use of ordinary linseed oil paints on rammed earth walls in the first edition of Bulletin 277. The results up to the time the first edition was printed in 1933 indicated that such a covering would prove satisfactory. As reported in a later bulletin, No. 298, many failures have occurred with these oil paint panels and in 1938 the results are still somewhat uncertain. The studies are being continued. At present the results indicate that a definite relationship may be found between the total clay colloids in the wall and the favorable use of oil paints. Since all soils that are very high in sand must be low in colloids it is probable that walls built from such soils may be safely painted. No failures of oil paints have occurred on walls containing 75 per cent or more of sand, up to the present time. On the other hand all oil paint panels have failed on walls containing less than 40 per cent of sand and more than 25 per cent of clay, and on all walls containing higher than 35 per cent total clay colloids. Oil paints on walls in between these two limits have varied in their behavior. Dark colored paints as would be expected, seem to be more resistant than light colored paints and some dark paints have stood satisfactorily for three or four years on walls containing only 50 to 60 per cent total sand. Two panels on north exposures are still in perfect condition after five years but duplicate panels on south exposures showed the first signs of failure in three and one-half years. These two panels are on walls containing approximately 50 per cent total sand. Paint panels on walls containing less sand stand intact for approximately two years before showing the first signs of failure. On walls of high clay colloids oil paints will stand perfectly for one to two years and will then begin to fail badly. On very heavy clay soils even stucco will fail but these are soils that are unfit for use in pisé walls. As stated elsewhere in this bulletin a soil containing more than 40 per cent total clay colloids is entirely unfit to use for rammed earth walls. Only a small percentage of soils fall into this class.

The above discussion applies to outside or exterior surfaces only. Almost any paint will stand satisfactorily on an interior wall under reasonable moisture conditions. At the present time only three reliable external coverings for medium quality soils have been found, out of nearly one hundred materials tested.[14] These are ordinary stuccoes, and plasters.

14 These covering tests will be reported in a later publication.

Cement Stucco.—Probably all stuccoes which are used on other surfaces today will prove satisfactory on rammed earth walls. However, our tests have shown that for Portland cement stucco a slightly leaner mixture of cement and sand is better. A mixture of (1-4-¼) one part of Portland cement, four parts of sand, and one-fourth part of cem-mix or mortar-mix by measure, is possibly best. Before applying the stucco the earth wall is sprayed lightly with water and as soon as each coat of stucco has set hard enough so that it will not be marred by the spray it is wet down. The stucco surface should be kept moist for two or three days if possible (as is the case with any stucco wall) and it is a good practice to shade it from the sun, especially when the stuccoing is done in hot weather. Two satisfactory ways of bonding the first or "scratch" coat of stucco to the earth wall have been used on wall panels six feet high. One way is by means of metal lath or stucco reinforcing wire. This reinforcing is nailed directly to the wall with 16d nails spaced approximately 12 inches apart each way. Where splices are made in the reinforcing a good lap should be made and the wires well spliced together. This method is advised for dwelling houses and for high walls. An experienced stucco man should be secured for applying stucco in this manner. The other method of applying stucco to rammed earth walls is by nailing the first or scratch coat directly to the wall immediately after it is spread. This method has been used on walls from six to eight feet high and the stucco is standing quite satisfactorily after four years of service. The nailers should follow directly behind the plasterer and two men are apt to be needed. Twelve to sixteen penny nails should be used, depending upon the hardness of the wall and they should be driven approximately 12 inches on center and preferably at random. The heads of some of the nails may be left extending an eighth of an inch to help in bonding the second coat. One experienced and successful

Figure 19.—THIS GARDEN WALL OF RAMMED EARTH WAS BUILT IN 1934 AND WAS STUCCOED IN 1935.

The soil used in the wall is only medium in quality and hence, must have a protective covering. The picture was taken before stuccoing. The wall is an experimental wall and today carries 28 panels on which different methods of bonding the stucco to earth walls are being tried. The wall is around the garden of the President's home.

stucco man asked that this be done and claims that such a stucco job will be superior to other methods. These two methods and the spacing and size of nails used are selected after fourteen different methods of bonding stucco were tried on 28 test panels. The second coat of stucco may be applied in three or four days after the first and a third finishing coat or dash coat may be given if it is desired. For a farm building or poultry house a sand finish may be satisfactory. This finish is made by means of a carpet float. The surface is allowed to partially set-up as in the case of a concrete floor. It is then dampened and worked with a circular motion and with a wood float covered with a piece of commercially woven carpet.

Dagga Plaster and Paint.—Dagga plaster is a fairly good temporary covering for an earth wall, and it may be made quite permanent by painting with outside house paint and by keeping it well painted. Dagga plaster is made out of sand, clay, and water, mixed into a slightly dry mortar (nothing is added) and plastered onto the earth wall. It should be applied to the wall in exactly the same manner as stucco, except that it does not need to be wet down and kept moist as is the case with stucco. Two parts of sand screened through a No. 12 screen are mixed with one part of average to light clay soil in making dagga plaster. This clay should contain at least 37 per cent of sand as tested according to the simple test for rammed earth soil as outlined earlier in this bulletin. If unaquainted with the materials a small sample batch should be measured and mixed into a mortar, slightly dry. A smear of this mortar more than a foot in diameter should be made on the wall and left stand for two or three days in drying weather. If it dries without cracking it is satisfactory to use and if checks appear, slightly more sand should be added and a second trial made. Two coats of dagga plaster should be applied and in four or five days it should

Figure 20.—AN EXPERIMENTAL WALL FOR PAINTS AND PAINTING METHODS.
This garden wall is divided into 28 experimental paint panels. The paints were applied at different periods, in different weight and number of coats, and over different priming coats. Different soils were also used varying from excellent to very poor in quality. The report on these and other covering panels should be available in a special Experiment Station bulletin on coverings about August 1939.

be painted. Before using the linseed oil paint the plastered surface should be "sized" or primed by brushing on a thin coat of glue sizing. This sizing solution is made by dissolving cheap commercial glue in hot water at the rate of one pound of glue to each gallon of water. After two days the wall should be given a slightly thinned coat of a good grade of linseed -oil lead paint. The second coat of paint is applied as for any surface. The priming coat of glue sizing is slightly slow in brushing on but after that the other coats go on easily. Owing to the roughness of the surface they should be brushed out carefully, in order to get the coat on evenly. Paint on the above dagga plaster has stood without any sign of failure for six years and has been used on several large panels.

Dagga Plaster Plus Portland Cement.—Another reliable plaster for earth walls that has been tested at this station is dagga plaster to which is added 10 per cent of Portland cement. One shovel of cement is added for each nine shovels of the sand and clay soil, mixed together. A slightly stiff mortar is made up of this mixture and applied in two coats in the same way as stucco. The first coat should be nailed as for stucco and the plaster will be improved if protected from too rapid drying of the surface.

Linseed Oil Paint on Walls of High Sand Content.—As stated above outside house paint has not failed on any pisé wall containing 75 per cent or more of sand. The paint is applied over a priming coat of glue sizing and in exactly the same manner as outlined above for painting dagga plaster. Indications up to the present time are that two medium coats of paint are better than two extra heavy coats. Oil paints may be applied to rammed earth walls at any time after the forms are removed from the wall section. Possibly the best time to paint the wall is between three to thirty days after it is rammed. Fourteen paint panels were used in a study of this time factor and the intervals tried in the test ranged from

Figure 21.—WETTING DOWN A RAMMED EARTH WALL BEFORE PLASTERING.
Before plastering the earth wall it is wet down so that the moisture will not be drawn from the plaster. A garden sprinkler could be used in place of this small spray machine.

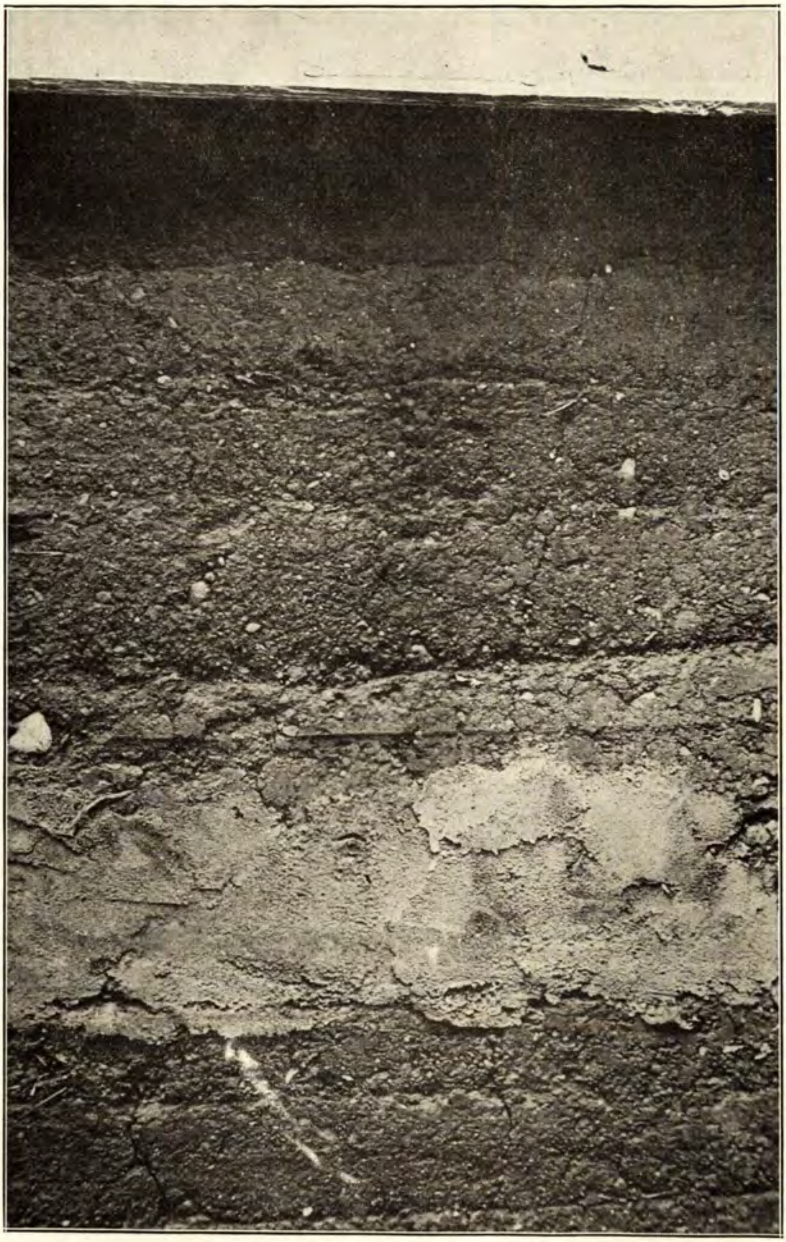

Figure 22.—REPAIRING HOLES IN A RAMMED EARTH WALL.

Repairing holes or other defects in a rammed earth wall is easily and quickly done with portland cement mortar. Such a repair is shown in the above picture. The mortar is made by mixing one part of cement with four parts of sand and making a rather stiff dry mortar. The surface should be moist before applying the mortar. An extra safety measure is to drive a few old nails in the bottom of the hole to be repaired leaving the heads stick up about one-half inch.

one day to one year, with no advantage resulting. Note: In order to avoid confusion of material the original detailed report on coverings contained in this bulletin has been omitted from this edition and will appear in a subsequent bulletin devoted entirely to protective coverings for earth walls.

Interior Wall Coverings.—Probably any satisfactory covering can be used on interior walls of rammed earth. They can be applied directly to the earth surface. Both oil paints and cold water paints have been successfully used. All ordinary plasters are entirely satisfactory. For extra safety the scratch coat of plaster may be nailed with 10 d. nails in the same way as for stucco. The only two failures in inside wall coverings that have occurred have been with a special wood, fibre plaster and whitewash—a cold water paint. Murescoes are quite satifactory. They, as well as oil paints, should be applied over a glue sizing coat.

Weight, Shape and Type of Hand Rammers

After three years experience in the use of hand rammers of various shapes, sizes and weights, the favored rammer is one with a cast iron or steel head cubical in shape and approximately 3 inches in dimension each way. The shaft of this rammer will be of one-inch galvanized iron water pipe and approximately 5 feet 6 inches long. The total weight of this rammer will vary from 13 to 18 pounds. The face of the rammer will be perfectly smooth and flat, and the weight of the rammer will be from 1.5 pounds to 2 pounds for each square inch of the rammer face. This rammer will be well balanced with a shaft easy to grasp and hold and one that will quickly wear to a very smooth surface. The inch pipe may be threaded and screwed into a plate made from a pipe flange that is in turn fastened to the iron block by means of screw bolts, or the pipe may be brazed or welded to the head. Welding the shaft to the head will be best when the materials are suitable, as the flanges will sometimes fail after long use. The square rammer is favored because corners and edges of the form can be better reached with it and the flat rammer is not only favored by the workman but test pieces made with the flat-faced rammer have shown a greater average strength in compression.

In order to compare the effectiveness of that flat faced rammer with those having sharp faces a careful test was made. Three shapes of rammer faces were used. One[15] has a sharp face in which the sides make an angle of 45° with the horizontal, one has a fairly sharp face in which the sides make an angle of 30° with the horizontal, and has a flat face. Five test blocks were made with each rammer and tested to failure in a compression machine. An identical soil, test soil No. 2, having a total sand content of 37.5 per cent, was used and the moisture content was kept uniform. The blocks made with the flat rammer were strongest, those with the 30° rammer averaged next in strength, and those with the 45° rammer showed the least strength. These results are shown in Table No. 5.[16]

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15 See Fig. 4.

16 It is true that with flat faced rammers the planes of cleavage between layers of earth in the walls are quite apparent and the shearing strength is probably less than if wedge shaped rammers are used, yet the strength is entirely satisfactory. No trace or suspicion of failure has developed in any of the more than 1,000 feet of walls that have been built during the past eight years either in straight experimental walls or in buildings. One experimental building has been constructed with a roof truss that throws a maximum roof thrust upon the rammed earth walls. The walls are standing perfectly after three years.

Figure 23.—A SHELTER FOR PROTECTING THE SOIL USED FOR RAMMED EARTH WORK.

In a shelter like this the dirt can be kept dry enough to work at all times. A heavy rain on unprotected dirt will make it too wet to use for days and even for weeks. If a shelter is not available a canvas or other protection is necessary. The material used in building this shelter was all used in the roof and plate construction after the walls were finished.

Table 5.—Comparative Strength of Test Blocks Rammed With Different Shaped Rammers (Compressive Strength)

Shape of Rammer Face	Ultimate Load of Test Blocks in Compression (Average)	Compressive Strength Lbs. Per Sq. Inch	Age When Broken (In Days)	Total Sand Content (Per Cent)	Number of Blocks of Each Broken
Sharp-faced Rammer Sides 45° with horizontal	28,457	351.3	40	37.2	5
Sharp-faced Rammer Sides 30° with horizontal	40,219	496.5	40	37.2	5
Flat-faced Rammer	44,107	544.5	40	37.2	5

Intensity of the Tamping Stroke

A study was made to determine the effect of the intensity of the ramming stroke upon the compressive strength of rammed earth. Test blocks were made in the standard form. Five blocks were made using light strokes, five were made using medium strokes, and five were made using heavy strokes. A supply of soil was carefully prepared for these blocks containing 38.22 per cent of total sand and 61.78 per cent of silt and clay by weight. This is very nearly an average soil and contained 9 per cent of moisture when used. This moisture was perhaps slightly under the optimum amount. The blocks were rammed in four layers of equal weight, making the weight of the finished blocks almost identical. The depth of the finished blocks varied inversely with the intensity of the tamping stroke used in making them (see Table 6). Approximately 100 strokes were used in tamping each layer although a fewer number would have been sufficient for the harder strokes. For the light strokes the rammer was raised about four inches and no exertion used in making the stroke. For medium strokes the rammer was raised about six inches and very little pressure was applied. For the heavy strokes the rammer was raised about 12 inches and all the force possible applied with the stroke. As shown in Table No. 6, the compressive strength of the blocks varied directly with the intensity of tamping and was decidedly in favor of the heavy tamping. The five lightly tamped blocks averaged 92.6 pounds per square inch in compression. The five medium tamped blocks averaged 189.1 pounds per square inch, while the five heavily tamped blocks averaged 448 pounds per square inch. Extremely heavy strokes are not necessary for rammed earth construction, although it might show a slight increase in the strength of the wall, but this study indicates that some little pressure is needed on the rammer especially near the beginning and at the end of the tamping of a new layer. If pressure is not used the bottom of the layer will not be compressed sufficiently. It is entirely probable that the weathering resistance of the wall will also be greater for the heavier tamping, and especially so if no protective covering is used. On the other hand the more lightly tamped wall would be the best insulator.

The strength of the blocks runs quite uniformly for each group, seldom varying more than 10 per cent from the average figure. One exception was with one of the blocks made with a medium tamping stroke. This block tested only 82.90 pounds, which was only half the average strength and probably due to some unnoticed defect. It was averaged in with the rest as it would affect the average figure but slightly.

Table 6.—Effect of Intensity of Tamping Stroke Upon Strength of Rammed Earth

No. of Blocks of Each Tested	Intensity of Stroke	Av. Ultimate Breaking Load in Pounds	Compressive Strength lbs Per Sq. in.	Depth of Blocks When Made (Av.)	Weight of Blocks When Made (Av.)	Unit Weight Per Cu. Ft.	Moisture When Broken (Av.)	Age When Broken (Days)
5	LIGHT	7,506	92.7	11.14 in.	56 lb	108	2.1%	44
5	MEDIUM	15,320	189.1	9.97 in.	56 lb	125	2.7%	44
5	HEAVY	36,280	393.4	8.94 in.	56 lb	135	2.9%	44

Size of Aggregate in Soil for Rammed Earth Construction And Its Effect upon the Compressive Strength

The fact that a considerable amount of aggregate is desirable in soil for rammed earth work led to this study to determine the effect of different sizes of aggregate in rammed earth walls. Experimental Soil No. 1 was used for the base soil. It originally contains 10.4 per cent of fine aggregate. This base soil was mixed with sufficient moisture to bring the moisture content up to 16.01 per cent. The aggregate that was added was then moistened before it was mixed with the soil for ramming into the form. In having the base or bonding soil at the same moisture content and in moistening the aggregate before mixing, it was figured that the results would be most comparable. This accounts for the decidedly higher moisture content in the check blocks because the addition of aggregate reduces the moisture content decidedly. The larger sized aggregate having less surface area reduces the moisture more than the smaller sizes as shown in the table.

Two different series of blocks were made for this study. In the first series, made more than a year earlier than the second, only three different sizes of aggregate were used. Thirty-five per cent (by weight) of aggregate was added to the 10 per cent already in the base soil in each instance bringing the total up to 45 per cent. Four standard sized test blocks, each 9x9x9 inches high (approximately), were made for each different sized aggregate, viz., four with aggregate ranging in size from 0 to one-eighth inch, four with aggregate ranging in size from one-eighth to one-fourth inch, and four with aggregate ranging in size from one-fourth inch to one-half inch. The figures are given in table No. 7 along with the figures from the more complete similar series for the purpose of showing the similarity in results.

The second series of blocks for this study was made in the same way using the same base soil. In the second series thirty-five per cent of aggregate was added as in the first series and two additional sizes of aggregate were included. The blocks were tested to destruction in a Riehle testing machine, described earlier in the bulletin. Owing to the nature of

Table 7.—Effect of Size of Aggregate in Soil on Compressive Strength of Rammed Earth

No. of Blocks of Each Tested	Weight of Blocks—lbs Av.	Moisture Content When Made	Moisture Content When Broken	Total Aggregate in Soil	Age When Broken (days)	Size of Aggregate Added (35%)	Average Ultimate Breaking Load in lbs.	Compressive Strength in lbs. Per Sq. In.
First Series								
4	56.2	12.89%	3.88%	45%	54	0 in. to ⅛ in.	28,956	359
4	55.8	12.45%	4.06%	45%	54	⅛ in. to ¼ in.	31,428	388
4	55.7	13.31%	4.28%	45%	53	¼ in. to ½ in.	26,804	330
Second Series								
4	43.6	16.01%	6.21%	45%	60	None	23,757	293
4	54.6	12.04%	3.38%	45%	60	0 in. to ⅛ in.	25,345	313
4	53.8	11.51%	3.43%	45%	60	⅛ in. to ¼ in.	27,010	333
4	54.2	11.22%	3.82%	45%	60	¼ in. to ½ in.	17,452	216
4	54.8	10.8 %	4.01%	45%	55	½ in. to ¾ in.	18,547	229
4	54.7	11.81%	4.28%	45%	60	¾ in. to 1½ in.	13,370	165

the surface of the test blocks it was impossible to read the point of incipient failure with sufficient accuracy, so the ultimate load only is given. Space will not permit showing the strength figure for each individual block but they showed a surprising uniformity of strength for each series, varying only slightly from the average figure. The soil having the one-eighth to one-fourth inch sized aggregate showed the greatest strengh. The 0 to one-eighth inch size was second in strength. The check blocks with no added aggregate came third in strength and the others came in the following order: one-half to three-fourth inch, one-fourth to one-half inch, and three-fourths to one and one-half inches. The only questionable variation in the curve was in the size one-half to three-fourths inch going above the one-fourth to one-half inch size in strength, although these two were very nearly the same. The figures bring out the unquestioned fact that aggregate in rammed earth soils up to one-fourth inch in size and in quantities up to 45 per cent will increase the compressive strength of the structures. It also clearly shows that aggregate larger than one-fourth inch in size, although desirable in reasonable quantities, will decrease the strength of rammed earth structures when used in quantities as high as 35 per cent.[17]

Effect of Adding Lime

A brief study was made to determine the effect of lime on rammed earth. Pure hydrated lime was used and mixed with a carefully prepared soil made up of 62.5 per cent silt and clay, 37.5 per cent total sand and with 10 per cent moisture. To the lime was added just enough moisture to give it the same apparent moisture as the soil. A carefully weighed amount of lime was added to give each series of test blocks the following percentage of added lime: Three blocks with 1% of lime, three blocks with 2% of lime, three blocks with 3% of lime, three blocks with 4% of lime, three blocks with 5% of lime, three blocks with 10% of lime, and three blocks containing no lime for checks. The blocks were rammed in four layers. Fourteen pounds of the mixture was weighed for each layer of the blocks and the final blocks averaged approximately 56 pounds each. The test blocks were rammed on November 26 and December 3, 1932 and broken on January 7, about five weeks later. During this interval they were stored in the research laboratory under a temperature of approximately 70° Fahrenheit where the moisture was reduced to an average of slightly over 3 per cent as shown in Table No. 8. The added lime had the effect of causing the corners and edges of the blocks to crumble slightly and seemingly in direct proportion to the amount of lime added. This effect was so pronounced as to make the blocks delicate to handle, especially when they were removed from the trays and placed in the testing machine. The blocks were tested to failure in a Riehle machine to determine the effect of the added lime on the compressive strength of rammed earth. The operators used in ramming the blocks were interchanged when each layer was partly rammed, thereby eliminating any chance for a variable from this factor. The strength curve was not quite uniform as the table shows, but there is no doubt that the lime weakened the test blocks, as the check blocks which contained no lime were decidedly stronger. It is

17 Although the size of aggregate affects the compressive strength of pise' walls it seems to have no effect upon the weather resistance. Very fine sandy soils have proven highly resistant to weathering. Their strength is entirely sufficient for walls of reasonable height.

probable that the increment between the amounts of lime added should have been greater. Slight corrections were made for difference in the depth of blocks which in no case changed the order of the resulting strength figures. The results are summarized in Table No. 8.

Table 8.—The Effect of Adding Lime Upon the Strength of Rammed Earth Test Blocks
(Dimensions of Blocks 9 in. x 9 in. x 9 in.)

Number of Blocks of Each Tested	Amount of Lime Added In Per Cent	Av. Ultimate Break'g Load in Pounds	Compressive Strength in lbs. Per Sq. In.	Kind of Soil Used		Moisture When Made	Moisture When Broken
3	None	42,500	524	Silt and Clay Total Sand	61.78% 38.22%	10%	2.1%
3	1%	32,260	404	"	"	10%	2.6%
3	2%	27,250	356	"	"	10%	3.7%
3	3%	34,460	436	"	"	10%	3.4%
3	4%	33,340	435	"	"	10%	3.9%
3	5%	28,590	377	"	"	10%	2.0%
3	10%	30,760	405	"	"	10%	3.1%

Effect of Mixing Fiber with Rammed Earth upon Its Strength in Compression

A total of 28 pieces were made for this study. Experimental soil No. 2[18] was used for the base soil and the blocks were of standard size—9x9x9 inches. Corrections were made for slight differences in depth of blocks. These corrections made no difference in the comparative order of results. Three different kinds of fiber were added to these blocks viz., flax straw, oat straw, and grass sod (having had the dirt removed). A series of three blocks was made to which the flax straw was added. The straw was cut up roughly into lengths of about five inches. All the straw that could be mixed into the dirt without having it form in bunches was incorporated. Three blocks were made in the same manner using oat straw, and four were made using the grass sod. This series of blocks was then repeated using approximately one-half the amount of the same fibrous materials in the dirt. Eight check blocks were made containing no fiber and compared to the above blocks in compressive strength. The blocks containing the maximum fiber gave the greatest strength, or 416 pounds per square inch. Those containing one-half of the maximum fiber came next in strength with an average of 360 pounds per square inch, while the check blocks containing no fiber showed the least strength with 325 pounds per square inch. All factors such as ramming, moisture content and base soil were closely controlled. This study would indicate that there is some increased strength to be expected from adding fiber to the dirt in rammed earth work. In most cases there should be no need for it, however, and the fiber spoils the smoothness of the wall. It would interfere with some coverings that might be used and if no covering were used it would probably cause more rapid weathering of the wall surface. This finding agrees with the following statement made by Long of California in Exp. Sta. Bulletin No. 472—"With an alluvial loam soil, an admixture of approximately one-fifth part of straw by loose volume gave an increased strength amounting to 80 per cent in small specimens." There is a very great possibility that the straw, or fiber, if added to a

18 See Table No. 1.

Table 9.—Effect of Mixing Fiber With Rammed Earth Upon Its Strength in Compression
(Dimensions of Blocks 9 in. x 9 in. x 9 in.)

Number of Blocks of Each Tested	Kind of Soil Used	Moisture When Made Average	Moisture When Broken Average	Age When Broken	Amount of Fiber Added	Compressive Strength in Pounds Per Sq. In.
3	Silt and Clay 61.7% Total Sand 37.2%	8.93%	3.60%	46 da.	Maximum Oat Straw	485
3	" "	8.93%	2.04%	46 da.	Maximum Flax Straw	473
4	" "	8.71%	1.70%	53 da.	Maximum Grass Sod	357
					Maximum Fiber Av.	438
3	" "	8.93%	3.39%	46 da.	½ Maximum Oat Straw	429.6
3	" "	8.93%	3.30%	46 da.	½ Maximum Flax Straw	381
4	" "	8.71%	2.15%	53 da.	½ Maximum Grass Sod	299
					½ Maximum Fiber Av.	370
8	" "	8.71%	1.66%	53 da.	None	325

wall made from soil of very low sand content, might reduce the cracking of the surface due to shrinkage. This is being studied. The data is summarized in Table No. 9, above.

Rate of Drying Out of Rammed Earth as Affected by an Admixture of Fiber Such as Straw

Observation of test pieces of clay soils in which straw and other fiberous materials had been incorporated seemed to show less cracking and checking as they dried out. The logical reason for this fact seemed to be that the straw extending from the center to the outside of the blocks carried the moisture from the center of the block more rapidly than for those containing no straw. Heavy clay soils crack and check on the surface because the moisture from the outside layers is lost causing this portion to shrink first. If the moisture were lost from the center of the block or wall at the same rate as for the surface the cause for cracking would be removed.

This study was made to determine if an admixture of straw in pisé walls would aid in leading the moisture from the center to the outside of the wall and thereby reduce surface cracks and if so, at what rate as compared to walls with no straw. As is shown in Table No. 11 and by the curves in Fig. 24 the results indicate definitely that the straw does not reduce surface cracks by aiding the escape of moisture from the center of the wall. It has no appreciable effect upon the rate of drying out or moisture loss from the wall.

In the plan for this study three clay soils were selected and three test pieces were made in each case from which the average of the three pieces is recorded in the table and curve. Soil No. 1 is fairly heavy, black clay

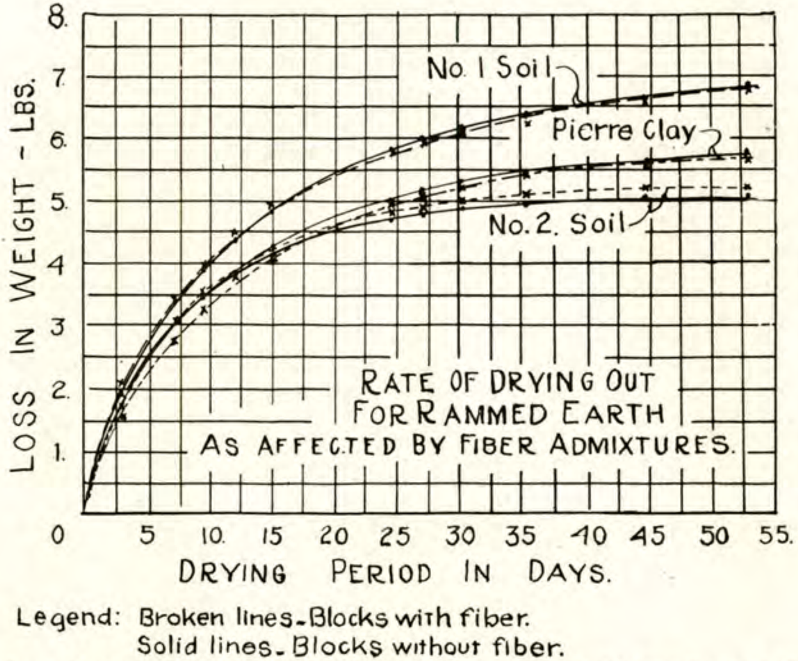


Figure 24.—THE ADDITION OF STRAW TO WALLS OF PUDDLED EARTH DOES NOT AFFECT THE RATE OF MOISTURE LOSS FROM THE WALL.

The 9x9x9 inch test pieces of three different soils dried out at the same rate regardless of the admixture of straw. Note the close proximity of broken and solid lines in the curves for each soil.

soil containing 40.4 per cent total clay colloids. The Pierre clay is a very heavy gray clay soil containing 50 per cent total clay colloids. Soil No. 2 is a medium yellow, sandy clay containing 37.3 per cent total clay colloids. Three "check" blocks were rammed from each soil without any admixture and three blocks were rammed from each soil to which was added all the straw that could be thoroughly incorporated in it. The amount was approximately 130 lbs. of straw to 1000 lbs. of soil. Oat straw was used and it was cut in lengths not to exceed six inches. The test blocks were all made on the same day and the moisture used in the clay was just slightly above optimum. The blocks were weighed immediately as they were taken from the form and placed on an air-dried board tray of known weight. They were then held at constant room temperature and weighed at the intervals shown in the table. They were handled on trays, and tray and all was weighed each time to avoid the loss on any of the material. The loss of moisture only is recorded in the table for purpose of simplification and the loss is recorded in pounds. The moisture loss ran uniformly with each individual test block and the very slight difference in the rate of moisture loss was apt to be in favor of the check block as with the block containing the straw admixture. Since this study indicates that moisture loss is not affected by the straw, and since it is quite evident that an ad-

Table 11.—Summary Sheet for Data and Curve on Rate of Drying Out as Affected by Fiber Admixtures

	Soil No. 1 Medium Clay* Loss of Weight in Lbs. to Date—Col. 1		Pierre Clay—Very Heavy* Loss of Weight in Lbs. to Date—Col. 1		Soil No. 2 Light Clay* Loss of Weight in Lbs. to Date—Col. 1	
Date Weighed	Av. of 3 Blocks With Straw	Av. of 3 Blocks Without Straw	Av. of 3 Blocks With Straw	Av. of 3 Blocks Without Straw	Av. of 3 Blocks With Straw	Av. of 3 Blocks Without Straw
Febr. 24, '34	(Date Rammed)	(Date Rammed)	(Date Rammed)	(Date Rammed)	(Date Rammed)	(Date Rammed)
" 27	2.12	2.01	1.58	1.75	1.94	2.02
Mar. 3	3.35	3.45	2.77	2.96	3.15	3.11
" 5	3.95	4.07	3.34	3.50	3.57	3.55
" 8	4.47	4.64	3.81	3.97	3.98	3.88
" 11	4.87	4.98	4.10	4.30	4.23	4.14
" 20	5.73	5.78	4.92	5.03	4.80	4.60
" 23	5.95	6.02	5.10	5.20	4.92	4.74
" 26	6.15	6.21	5.24	5.35	5.02	4.81
April 1	6.31	6.41	5.42	5.25	5.10	4.94
" 9	6.60	6.61	5.57	5.62	5.23	5.04
" 18	6.79	6.81	5.73	5.80	5.32	5.16

* A description of these three soils is given above.

mixture of straw does reduce cracking, it is therefore logical to assume that the straw takes up or absorbs a considerable amount of the shrinkage stresses due to its mechanical cushioning effect.

Reinforcing in Rammed Earth Construction

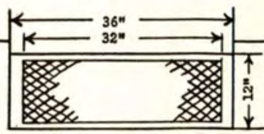
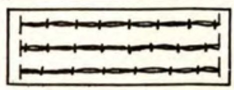
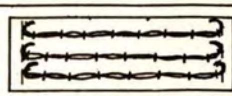
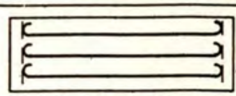
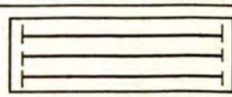
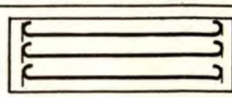
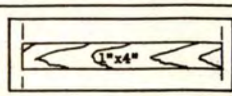
For the purpose of comparing the value of different kinds of reinforcing materials that might be used in rammed earth construction, fifty-one short beams were made, using eight different reinforcing materials. Seven of these beams were defective or broken in the making or hauling and were thrown out of the test. Three of these were the ones in which the use of boards was attempted. The test beams were 36 inches long, 12 inches wide and 7¾ inches in depth. They were rammed from Experimental Soil No. 2, having a total sand content of 37.5 per cent and a moisture content averaging 10 per cent when the beams were made. The beams were rammed in three horizontal layers or laminations with the reinforcing material embedded in the bottom layer at approximately one and one-half inches from the bottom of the finished beam. They were rammed in the bottom of the form that was built for making the small weathering walls.[19] A concrete floor furnished the bottom of this form. The reinforcing was placed in the following manner: The dirt for the first or bottom layer of the beam was first weighed out. Enough of this dirt was then shoveled into the form to make a layer of loose dirt two and one-half inches deep. This dirt was then leveled off and the reinforcing laid on top and pressed down slightly. The remainder of the dirt for the layer was then shoveled in and the layer rammed. The other two layers were then rammed on top of this one, giving a total depth of 7¾ inches for the beam. Two forms were used and two beams were rammed at the same time. This allowed for the interchange of workmen on each layer in order that any difference due to the ramming factor would be reduced to a minimum. The first trial was made with three beams for each kind of reinforcing. The second trial was made with five beams for each kind

19 See Fig. 9.

of reinforcing except that the beams with barbed wire with straight ends was not repeated. The second trial checked very closely with the first one throughout, and the results of both trials are combined and recorded together in the table. The beams average 256 pounds each in weight when they were rammed and they were handled on narrow slat trays approximately four feet long by ten inches wide.

They were broken in an Olsen testing machine as shown in Fig. 6. They were supported on two pieces of two-inch pipe which were placed exactly 24 inches on center, making the bearing points exactly two feet apart, and making the span two feet. A third short pipe was laid on the top of the beam exactly midway between the supports and the pressure was applied at this midpoint until the beam failed. An attempt was made to read the incipient load but fine checks that are often already present in earth beams made this figure somewhat uncertain and no figure is recorded in the table for it. For the check beams in which there was no reinforcing there was very little deflection as the load was applied until the point of rupture was reached and the beams broke rather squarely across. For the reinforced beams there was a very noticeable bending of the beam before failure. In most cases the deflection was sufficient to shear the layers of earth apart at the planes of cleavage which occur between each successive layer of the beam as it is made. Since the beams were supported in the test at a point six inches from the ends and since the strength figures desired were for comparative strength only, the weight of the beams was not included in the figures for the maximum moment. Two kinds of reinforcing materials that were tried decreased the strength of the beams materially. The beams with metal lath showed an average maximum moment of 229 foot pounds, while the three strands of barbed wire with straight ends gave an average figure of 321.5 foot pounds as compared to 370 foot pounds for the check beams in which no reinforcing was used. All the other kinds of reinforcing, except the boards, increased the strength of the beams materially and the strength varied as follows: Three strands of barbed wire with ends hooked, 489 foot pounds; three one-fourth inch round rods with ends hooked, 542.7 foot pounds; three one-fourth inch round rods with ends straight, 548 foot pounds; three one-half inch round rods with ends hooked, 878.5 foot pounds. Hooking the ends of the barbed wire increased the strength, while in the case of the rods there was no advantage shown. The figures are summarized in the following table and the arrangement of the reinforcing is also shown. Experimental Soil No. 2 was used in making these beams and a mechanical analysis of this soil is given in Table No. 1.

Table 10.—A Comparison of Reinforcing in Rammed Earth Beams
(All beams 7¾ in. x 12 in. x 36 in.)

No. of Beams Tested	Kind of Reinforcing	Manner of Placing	Ultimate Breaking Load in Pounds. Average	Maximum Moment in Foot Pounds. Average	Average Moisture When Broken
8	None		740	370	4.32
7	Metal Lath		458	229	3.89
3	Barbed Wire		643	321.5	3.3
7	Barbed Wire		978	489	4.59
7	¼" Round Rods		1091	542.7	5.01
5	¼" Round Rods		1156	548	4.28
7	½" Round Rods		1757	878.5	3.94
	Boards Laid Flat				

No results were obtained on the beams reinforced with boards owing to the fact that difficulty was experienced in keeping the beams intact for testing.

Figure 25.—THE MIXING BOARD FOR THE DIRT.

A mixing board is very convenient for turning the dirt when moisture must be added or when two or more different kinds of dirt are mixed for use. The board is almost necessary when the ground is muddy. It is approximately six by ten feet.

Figure 26.—PROTECTION FOR AN OUTSIDE WINDOW LEDGE.

A close-up view of an outside window ledge in a rammed earth poultry house wall. Note the metal strip nailed around the edge to force the water from heavy rains to drop from the outer edge. Without the metal strip this water will run back under the ledge and flow down the face of the wall. Bare walls will suffer damage from this water.

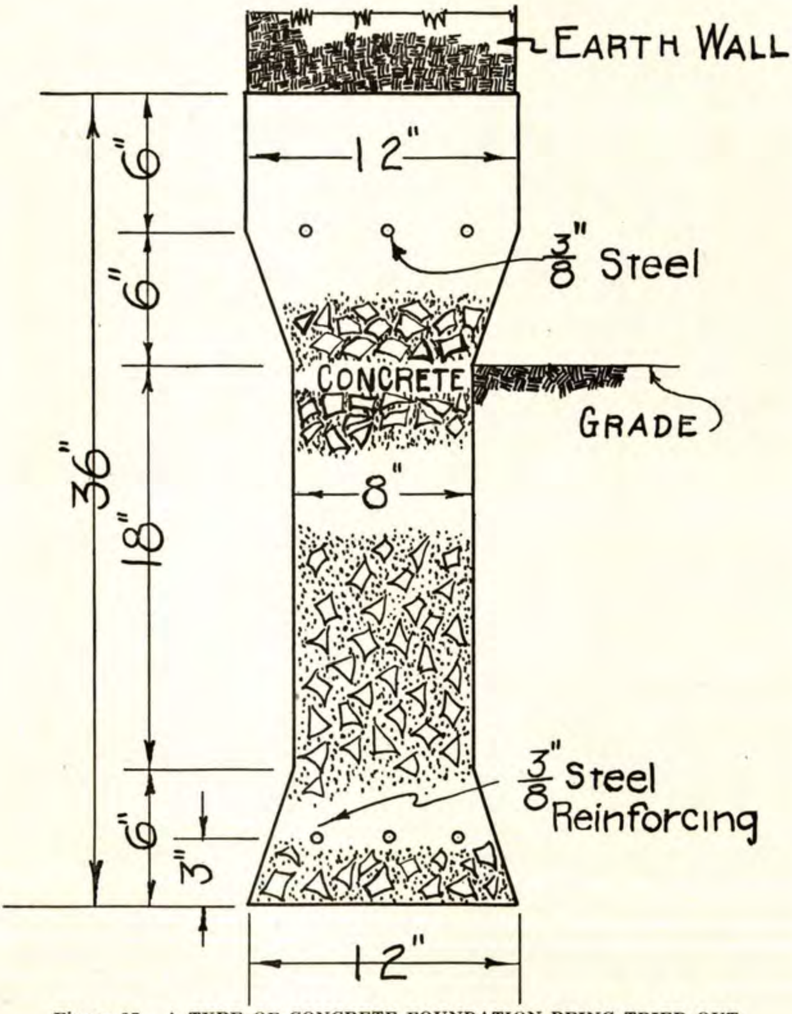


Figure 27.—A TYPE OF CONCRETE FOUNDATION BEING TRIED OUT UNDER LIGHT PISE WALLS.

Since the top of the foundation must be as wide as the earth wall, a saving of concrete can be made by reducing the thickness of the foundation between the top and the footing. In a well drained location the reinforcing rods would be unnecessary if the concrete mixture is good. For walls over 8 ft. in height the full width should be carried down from the top of the foundation more than 6 inches. This distance should increase slightly with the height of the wall.

Foundations for Rammed Earth Walls

The study has shown the necessity of good solid masonry foundations for rammed earth walls. If moisture soaks into the wall the physical structure of the soil changes. The wall will tend to expand and soften in much the same manner as a hard clot of dirt will soften after a rain except of course very much more slowly. A foundation is necessary to prevent capillary moisture from entering it from below. The wall is heavy, weighing on an average of 120 pounds per cubic foot, and the foundation must be strong. The foundation must also be as wide at the top as the thickness of the wall. All foundations used have been of concrete and have been found very satisfactory. Since rammed earth walls are 12 to 24 inches in thickness, and since the foundations should be the same thickness, such foundations must be expensive to build. It has been generally recommended that foundations in frost areas extend below the frost line for rammed earth walls. For dwelling houses and large buildings this practice should be followed. Steel reinforcing rods are also recommended in the footings for such buildings. Thick foundations of such depth would be almost prohibitive in cost for small farm buildings. Tests were made to determine how deep a foundation of concrete is necessary in this region. Another test was made for reducing the cost of foundations for light buildings by using an 8 inch foundation widened at the bottom for a footing and widened again at the grade line to the thickness of the wall. The plan is shown in Fig. 27 and no absolutely definite conclusions have been drawn as to its practicability. However, no disadvantages are evident as yet.[20]

Testing for Required Depth of Foundation for Rammed Earth.—For testing the necessary depth of masonry foundations for light farm buildings, three long test walls were constructed each five feet in height and each having a 30 inch wing on each end, thereby making two corners for each wall. These walls were rammed on concrete foundations of different depth and with somewhat different treatments. Following is a description of each of these foundations:

Foundation No. 1: This foundation was made from a concrete mixture of 1:3:6, or one part of portland cement, three parts of sand, and six parts of gravel. The foundation was 12 inches wide and 24 inches high, with only 12 inches extending below the ground level. It was 22 feet 6 inches long. No steel reinforcing was used in this foundation and no waterproofing coat was used on top of it. The foundation carrying a five foot rammed earth wall is well into its third year and is in perfect condition.

Foundation No. 2: This foundation was made of a concrete mixture 1:3½:7. It was made 12 inches wide and 36 inches high, with only 24 inches of it extending below the ground level. It was approximately the same length and had the same wing walls as No. 1. Four ⅜ inch steel reinforcing rods were used in this foundation. Two rods were placed in the foundation four inches from the bottom and two were placed four inches from the top. Since a coat of waterproofing has been recommended for the top of the foundation walls to break a possible passage of capillary moisture from below, the top of this wall was given a thorough

20 The type of foundation shown in Fig. 27 has proven entirely satisfactory up to 1938. It has been used under three buildings, with walls up to 10 feet in height.

coating of a heavy asphalt preparation. This foundation carrying a five foot wall is in perfect condition.

Foundation No. 3: This foundation was made of a concrete mixture of 1:3½:7. It was 12 inches thick and 48 inches high with 36 inches of it extending below the ground level. It was approximately the same length as the other two and carried the two wings. Four ⅝ inch steel reinforcing rods were used in this foundation. Two rods were placed in the foundation four inches from the bottom and two were placed four inches from the top. Instead of the water proofing coat used on Foundation No. 2, the top of this foundation was covered with a three inch layer of rich concrete mixed in the proportion of 1:2:3, or one part of portland cement, two of sand and three parts of gravel. This layer was troweled to a smooth surface. The foundation also carries a five foot rammed earth wall. It is in perfect condition and to the present time shows no advantage over the shallower foundations. The purpose of using the lean mixtures in Foundations No. 2 and 3 was so that they would crack more readily under a stress from heaving of the ground, and thereby indicate effect of the heaving forces. It is not a recommended mixture for rammed earth foundations.

A Test for Recording the Movement of Foundations Due to Frost Action.—The reason for deep foundations under light masonry walls in northern climates is to protect the wall against heaving forces. For low walls a shallow foundation in clay soils should be entirely stable providing is is not moved by such frost action. A movement of the foundation would be especially detrimental to a rammed earth wall that was stuccoed or plastered. In order to test for a movement of the foundations, steel indicators were embedded in the foundation ends and a bench mark set between each pair of walls. With this equipment the slightest movement of the foundation could be detected. The bench marks were made of steel rods packed in sand and extending to a depth of 8 feet. These three foundations are into the third winter and no movement of any of them has been recorded. The foundation that was narrowed to 8 inches between the footing and the grade line was used under an experimental poultry house with rammed earth walls and it has not been under test long enough for drawing conclusions as to its practicability. No objection to it or sign of failure has been observed to date.

The purpose of this foundation study was in the interest of strict economy. It indicates that it would be entirely practical to build light walls up to 8 feet in height and 12 inches in thickness on a concrete foundation as shallow as 18 inches below grade. This assumes that the subsoil is clay, that the ground is well drained, and that the concrete mixture is good. Not more than three parts of sand should be used in the concrete mixture to one part of cement, and the mixture should not be so wet as to be sloppy. Gravel or crushed rock can be added to this mortar up to five parts. If the location is not well drained the concrete mixture should be one part of cement, two and one-half parts of sand, and five parts of gravel and the foundation should go somewhat deeper, depending upon the conditions.

The masonry foundation should extend high enough above the grade so that water running from the eaves of the building will not splash up against the wall if no protective covering is used. This distance should be at least 12 inches.

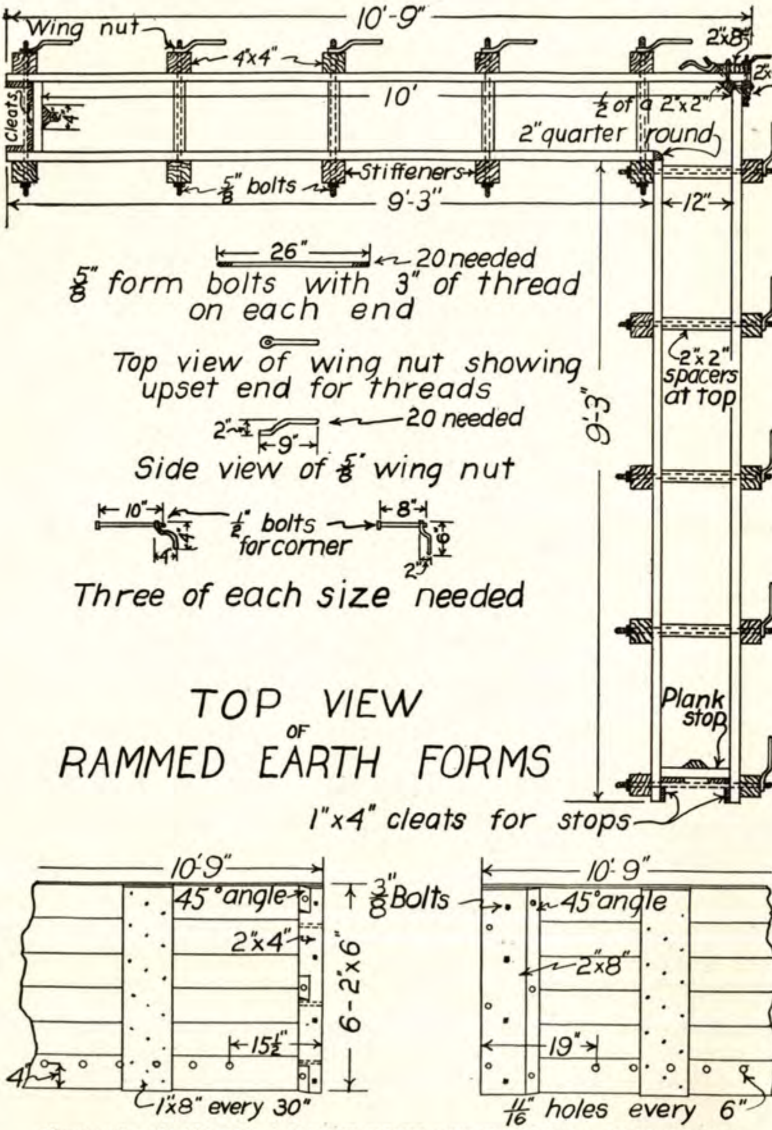


Figure 28.—PLAN FOR A LARGE FORM FOR RAMMED EARTH WALLS.

A drawing of the large forms for rammed earth which were used in building the rammed earth poultry house, showing dimensions of the form for making a wall 12 inches thick. It also shows the dimensions of form bolts and wing nuts. The nailing cleats are not shown in the "top view."

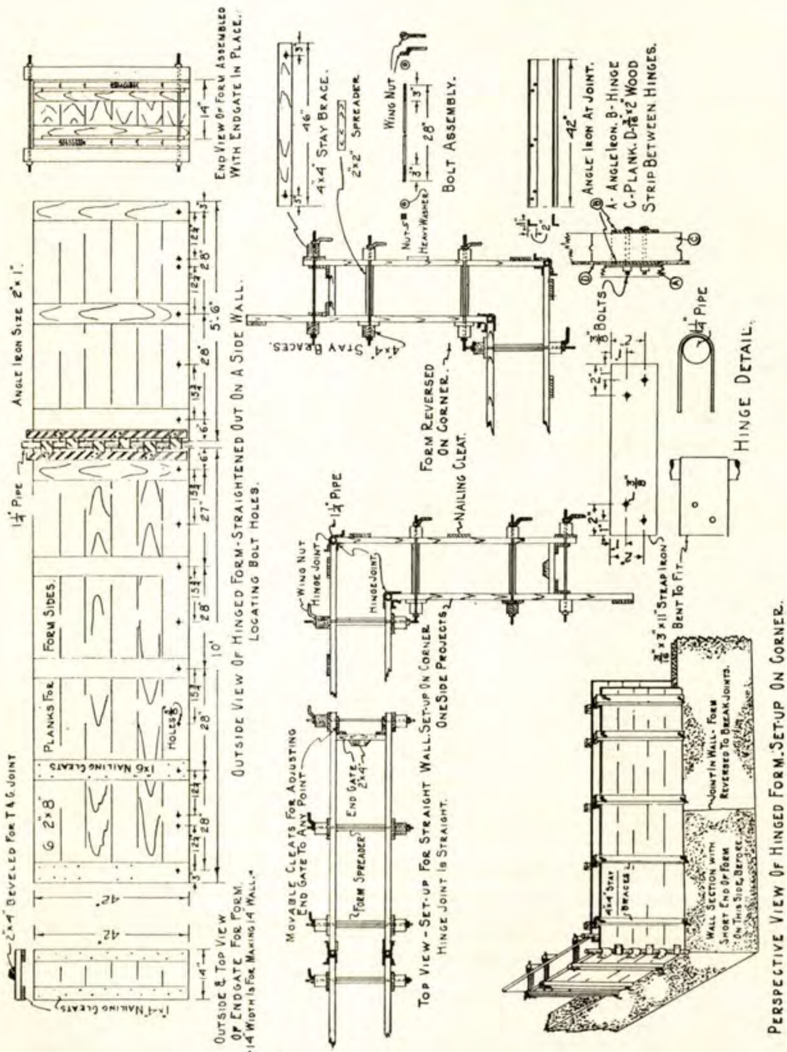


Figure 29.—A PLAN FOR A HINGED FORM FOR LARGE WALLS.

This form has a gas pipe hinge for building corners having any angle. Otherwise it is similar to the regular form shown in Fig. 28. The bolt lengths shown are for a 14-inch wall and can also be used for a thickness of 16 inches. For thicker walls longer bolts would be necessary. (Designed by H. DeLong.)

Waterproofing the Tops of Foundations.—There is no question but that the rammed earth wall must be protected from capillary moisture which might enter the wall from below. In the study an attempt was made to compare methods of waterproofing the tops of foundations but so far no moisture effects are evident even in the untreated shallow foundations. In order to make this comparison some of the weathering wall foundations were treated on top with asphalt while others were left unprotected. Certain sections of foundations were treated also, while other sections were left untreated. While the study thus far has shown no sign of capillary moisture coming up through a concrete foundation of a reasonably good mixture, the cost of a waterproofing coat of heavy asphalt or tar is slight and the practice is a good safety measure. This is especially true in regions of heavy rainfall. No doubt the layer of rich concrete used on the top of Foundation No. 3 mentioned above, would be equally effective for this purpose. In the case of a heavy building where a deep foundation of a rich mixture of concrete is used there would be no danger from capillary moisture and no need for waterproofing.

Forms for Pise' Walls

Forms for rammed earth wall construction must not be made of material less than 1½ inches thick. Two inch planed lumber is satisfactory. Since only one form of such dimensions as shown in Fig. 28 is necessary for making a complete building, the expense is not excessive. In 1938 the form shown in Fig. 30 is still in use after six years of service and has been used for building walls equivalent to six or eight poultry houses. It is in good condition today. Those who have built forms for rammed earth work have found a ready rental for them.

Forms used at this station are made of tongued and grooved plank, but it is not absolutely necessary that the plank be tongued and grooved. However, it is necessary that the planks be straight and not warped so that they will fit together and make a straight side wall for the form. It is also true that the forms will last longer and remain in better condition if tongue and grooved plank are used. It is important that these side walls be straight and true or much trouble will be encountered when trying to level the forms so as to obtain a straight wall. As soon as the forms are finished they should be given a coat of linseed oil to prevent the lumber from drying and warping. Furthermore, whenever the forms are not in use, particular care should be taken to see that they are standing or lying in such a way that they will not warp. That is, if they are left leaning against a wall the top part of the form should be touching the wall its entire length. If the forms are allowed to become warped, it is extremely difficult to level them onto a wall.

Linseed oil is a good oil to put on the forms immediately after they are made, and this may be followed by a coat of ordinary outside house paint on the outside, if desired. Used crankcase oil that has been drained from a tractor is satisfactory for the inside if two or three coats are applied.

The outward thrust caused by ramming a wall is tremendous, making it necessary to use heavy stiffeners on each side of the forms.[21] These removable braces should not be more than 30 inches apart and should be from 4x4 inch stock. Stiffeners made from 3x4 inch stock were tried but

21 See Fig. 30A and 30B.

were not strong enough to hold, so 4x4 inch pieces were used and gave good service.

To insure making a straight wall it is necessary to use spacers between the outside and inside walls of the form as shown in Fig. 30A. To prevent sharp corners on buildings, a 2 inch quarter round was placed on the inside corner of the form and nailed to one of the inside walls of

Figure 30.—RAMMED EARTH WALL FORMS LEVELED AND CLAMPED TO THE CONCRETE FOUNDATION

A. The outside of the form showing the heavy 4x4 inch stiffeners, also the form bolts and wing nuts which hold the stiffeners against the form. Handles as shown on the forms are very convenient when handling and resetting.

B. The inside of the form showing the 1x8 inch boards which are fastened to the form with screws. These cleats hold the sections together after the form bolts and stiffeners are removed. At the right the wall-stop is shown just back of the form bolts. Cleats should also be nailed inside the form to hold the stop in place.

the form. This makes a two inch bevel on the corners of all buildings.

The stops[22] or ends of the form are movable to any point in the form and they must also be made of plank. The stop is placed inside the end of the form or at window or door openings to form an end to the section of wall being rammed. A 2x4 inch strip tapered off should be fastened to the inside of the stop so as to form a groove in the end of the section and thus provide a better bond with the next section of wall. It is also necessary to nail cleats inside the form to hold the stops at any desired place in the form, as shown in Fig. 30A.

Some special means must be provided for fastening the corners on the outside walls of the form. A satisfactory method used at this station is shown in Fig. No. 28. A 2x8 inch plank with one edge planed down to an angle of 45° was bolted to the end of one form wall. A 2x4 inch piece with three notches cut at 45° angles was bolted to the end of the other form wall. This arrangement allows for three bolts to cross the corner of the form and for three parallel with one side. This design is very similar to other designs but is slightly simpler than some others. It also allows a small adjustment at the corner when leveling the forms by tightening or loosening the bolts extending across the corner.

The over-all length of the form is almost eleven feet. If it is desired to make a building in which inside dimensions are less than the length of the inside wall of the form, it will be necessary to shorten the form. However, regardless of the length it will be necessary to use two inch material for the sides.

Oiling Forms.—The oil on the inside of the form seems to work off into the dirt while ramming, making it necessary to re-oil the inside of

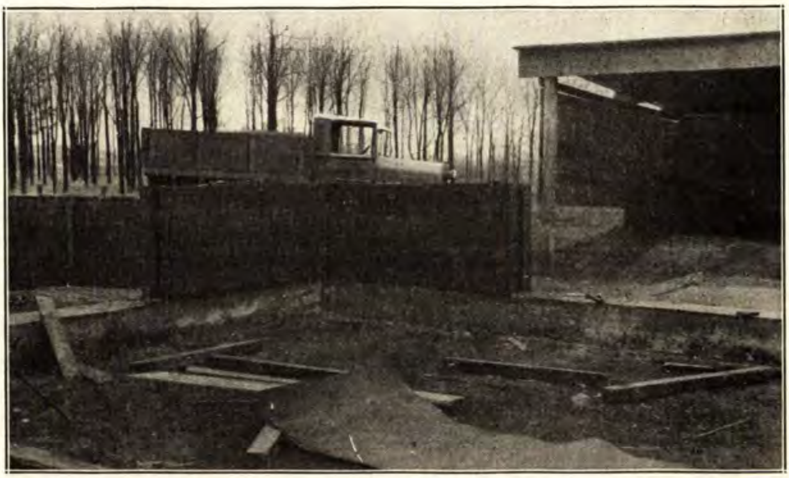


Figure 31.—A LARGE CORNER SECTION COMPLETED.

This shows the first completed corner section of a rammed earth wall in process of construction. The end groove is shown at each end of the section. When the adjacent sections are built these grooves will be filled and this joint makes the wall wind proof. At the right background is the shelter for protecting the dirt from rains.

22 See Fig. 30A and 30B.

the form. Used crankcase oil is satisfactory for this purpose. A light covering of oil is all that is necessary unless the soil used is wet. Wet soil will stick to the forms more than dry soils.

Leveling Forms.—In order to secure a straight wall it is necessary to level and plumb the side walls each time the form is set up. Sometimes both sides of the form will not be plumb or parallel to each other, so it is best to clamp the form to the foundation or preceding section of rammed earth, then level the outside form wall using the spacers to locate the inside wall. The bottom form bolts rest on the foundation or preceding section to hold the weight of the form. These bolts may be removed by pounding them, using a ½ inch rod for a punch after the section is finished.

The form should be set in place as shown in Fig. 30A and 30B with the form bolts loose. The stiffeners, spacers, and stops should be in place. Then by using a carpenter's level as shown in Fig. 30A, plumb the outside wall on each side of the corner. This may be done by either lifting the corner slightly or by lifting one end or the other as the case may be. When the corner is level, tighten the bottom form bolts next to the corner. Also tighten the upper bolts with spacers in place.

Then take the level to each end in turn and plumb up the end and clamp it solidly to the wall. After the corner and both ends are plumb, the form bolts along each side may be tightened. Care must be taken not to put any severe side thrust onto the form until after two or three layers are rammed in the bottom to help hold it in place..

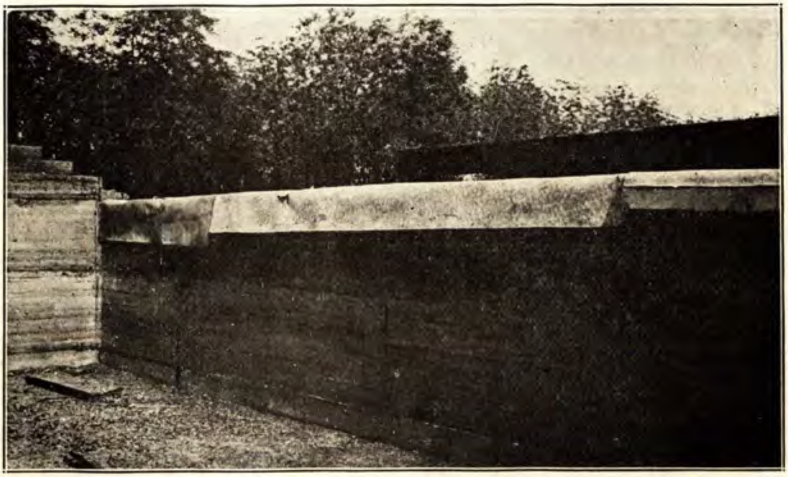


Figure 32.—PROTECTING THE TOP OF RAMMED EARTH WALLS DURING CONSTRUCTION.

The tops of rammed earth walls must be protected from rain at all times while the work is not in progress. Rain falling on the top of a pisé wall tends to soften it and when it flows down the side of the wall deep grooves will be cut. Strips of prepared roofing when available make an excellent protection. Light boards tacked along the edge of the strip hold it in place and protect it against the wind. This picture also shows the joints in the wall between the sections as they were built. At the lower center may be seen a wooden block embedded in the wall for a nailing tie.

Building a Rammed Earth Poultry House

Two buildings have been built of rammed earth, one a small experimental building in which several building practices were tried, the other a poultry laying house. The poultry house was built in farm size, being 16 feet wide by 32 feet long and having 12 inch walls all around. The house faced the south and was built after the plan (No. 311) of the "South Dakota Poultry House" having a two-thirds pitch or combination roof and a straw loft. A few slight changes were made in plan 311 for the rammed earth walls. The south side wall was made seven feet high and the north wall five feet, and the baffle-board shutter ventilators shown in the south side wall of plan 311 are made to fit into the window opening by raising the lower sash. This eliminated the extra openings in the south side wall that would have otherwise been required. Since the top of the foundation must necessarily be the width of the wall, the foundation was spread at the top and bottom, and a saving in concrete was made.[23] A concrete mixture of 1:2½:5 was used and the eight inch foundation was lightly reinforced with three-eighth inch steel rods at the top and bottom as a safety measure.

The house was built in the spring of 1932, between April 15 and June 6. The building of the walls, window and door frames, and the fitting of the plates was done by student labor at intermittent intervals (most of the work was done on week-ends), and practical methods such as would be used in actual construction were followed.

The Dirt Used.—Three kinds of dirt were used in the walls, the black top dirt that came out of the foundation trench, a yellow clay loam soil similar to Experimental Soil No. 2, taken from a basement excavation in the city, and a third yellow clay loam with slightly more sand in it. The soils were piled in the shelter so that they could be readily mixed on the mixing board, and they were mixed in the proportion that would afford a satisfactory moisture content, as some of them were drier than others. The mixing of these three soils was done by counting the shovels of dirt from each pile. No laboratory tests were made of the materials nor of the moisture in the dirt since it was desirable that the construction work be done under practical conditions. The proper moisture in the dirt was judged by the hand and by the way it worked under the rammer. In judging the moisture a handful of the dirt was squeezed together and dropped on a hard floor. It should stick together in the hand but when dropped on the floor it should break apart in small pieces when the moisture is right. If it is too wet it will stick to the rammer and will not ram down into a hard mass. A general idea of the amount of sand in each kind of soil being mixed was found by the practical test described heretofore, and the total sand in the final mixture probably averaged close to 30 per cent. This was not the optimum amount of sand. In fact it was rather low, and as expected the shrinkage joints were wider than had been experienced in the other large walls where the dirt used contained a larger amount of sand. The shrinkage joints were very easily filled later; some of them with earth and others with cement mortar.

Building the Wall.—Two forms were used on these walls part of the time, since they were available, although one large form is sufficient for a crew of three or even four men to work. The forms were first set up at

23 See Fig. 27.

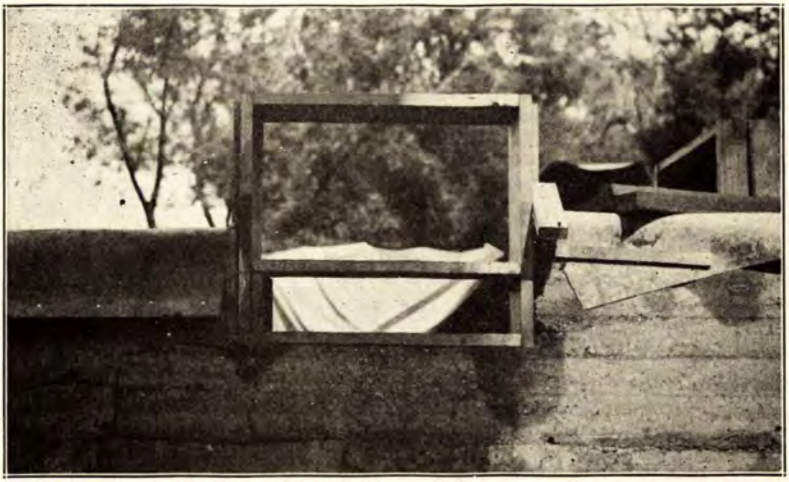


Figure 33.—SHOWING THE SETTING OF A SMALL WINDOW FRAME.

This picture shows the window frame set in place as the pisé wall is rammed around it. The frame is of 2x12 inch material and the 2x3 inch strips are shown nailed onto the sides next to the dirt. The earth wall was then rammed around these strips to make the joint wind proof. A heavy temporary brace of 2x12 inch material is shown set inside the window frame about eight inches from the bottom. This brace is very necessary and was raised when the sections above were built. When the dirt is rammed above the frame vertical braces are installed in a similar way.

the corners and rammed as full as desired. They were then moved along the foundation and set up for a second section of wall and continued around the foundation at this height.

It is very important to keep the forms level and plumb at all times and to finish the top of the section as level as possible as the lower bolts of the form rest on the top of the wall in placing them for the next course above.

Oiling and Filling the Forms.—The forms were first painted on the inside with a thin coat of used crankcase oil as already described. About four inches of loose dirt was then shoveled into them and leveled off, after which it was rammed until perfectly solid, and the process repeated. If the dirt does not ram until perfectly hard, the moisture is not quite right. It is probaly too wet. The dirt was mixed on the board, moved in a wheelbarrow and shoveled into the forms by one man, while two or three other men did the tamping. Care was used to have the soil mixed sufficiently to get the moisture content uniform throughout. The window frames, door frame and lower plate were all made from 2x12 inch plank, making them almost as wide as the wall. This was done for the added protection but it costs quite a little more than 2x6 inch material. The 2x6 inch material could be used in all places except for the door frames. By plastering or painting the inside portion of the wall not covered by the plate or frames it should be sufficiently protected. One other advantage in using the 2x12 inch frames however, is that the walls were rammed with the window frames in place and thereby getting a tighter fit. The frame was used for the end of the form and the earth rammed right up against it. A 2x3 inch strip was first nailed on to the outside of the window frame next to the dirt, so that this would make a tongue and groove joint around the frame. This three inch strip should be tapered to two inches at the outer edge so that the shrinking force will not pull it away from the frame to which it is nailed. The shrinking of the wall in some cases left open joints of one-fourth to one-half inch. These were filled and pointed up with mortar. The mortar was mixed 1 to 4 (1 part of cement to 4 parts of fine sand) and was mixed very dry so it would not shrink.

In ramming the dirt over the window and door frames an extra plank extending one foot into the wall at each end was used for a lintel.[24] The reinforcing study indicates that iron rods could be used satisfactorily for reinforcing here and that the practice would be a good one for wide openings. In ramming over door and window frames it is necessary to set vertical false posts or planks into the frame opening until the wall above is entirely finished. After the wall is finished, ordinary window frames were set into this rough frame for the 12-light, 10x12 inch pane, double hung windows. As the top course of wall was being built, long anchor bolts were embedded for bolting down the plate. These bolts were five-eighths inch bolts 15 inches long with a large flat anchor washer two inches wide by six inches long and one-fourth inch thick. The anchor washer was of course embedded at the bolt head at a depth of 12 inches in the rammed earth, leaving two or three inches of the threaded end extending through the wall for securing the 2x12 inch plate on top. Anchoring the plate is very important in rammed earth construction and extra large round washers were used under the nut on top of the plate for this

Figure 34.—PROTECTING THE TOP OF RAMMED EARTH WALLS DURING CONSTRUCTION.

This wall is expected to stand for 100 years without any protection after the roof is finished, but until that time the top of the wall must be protected at all times. Sisalkraft paper or old strips of prepared roofing are good for the purpose. The lower edge should stand away from the wall. Note the 2x6-inch vertical braces set inside the plank window frame to reinforce it while the wall was being rammed above it.

24 See Fig. 35.

reason. The plate was of double two inch thickness. The under plate was 2x12 inches and the top plate was 2x4 inches. The under plate only was bolted down and the 2x4 inch top plate placed at the outside was securely nailed to it. The top of the wall was leveled with a thick layer of Portland cement mortar under the first plate. The roof, concrete floor, straw loft and inside equipment were put in as for any frame house. The inside earth wall was plastered just where the birds could reach to pick it. Pure Portland cement plaster in the proportion of one part of cement to three of sand was used.[25] Two places were left unplastered on purpose to see how badly the birds might attack it, and as expected they worked on it in two or three places sufficiently to justify the recommendation for the practice of plastering. At one point a small hole has been picked in the wall to a depth of more than one inch. The band of plaster extended 30 inches above the floor and at the ends and back of the roosting alcove. Straight edge strips were tacked around the wall at the desired height for a gauge and a plasterer did the entire work in less than three hours time. The wall was lightly wet down with a spray of water just before plastering. In constructing the gable ends it was not considered safe to ram the wall on a slant or with the pitch of the roof, because with hard ramming the dirt breaks down to the lower level. The end was therefore rammed in horizontal sections leaving a notched effect** and these

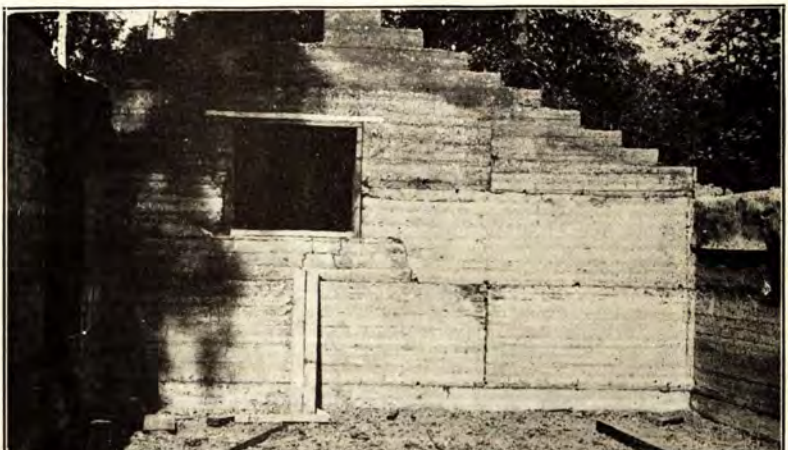


Figure 35.—THE FINISHED WALLS OF THE RAMMED EARTH POULTRY HOUSE.

This is an inside view of the poultry house walls showing one end. Since the gable end of the walls cannot be rammed very satisfactorily on the slant, or with the pitch of the roof, the end wall was notched as shown. The notches were filled with concrete between the frieze board and a form board placed inside as the roof was framed. The 2x12 inch plank over the heavy window frame was satisfactory as a lintel for a light wall. The opening at the peak above the window is for a small shutter ventilator.

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25 This plaster should have contained one-fourth part of cem-mix and 3½ parts of sand to 1 part of Portland cement. It should have been put on in two coats and the first coat should be nailed to the wall with 10d nails immediately after applying. The second coat should follow in a day or two.

**See Fig. 35.

notches were filled with concrete as the roof was framed. For poultry house construction the notches might be made larger, thereby requiring fewer settings of the form. The author urges the use of rammed earth or of rammed earth blocks for the gable end of the buildings.

Protecting the Walls During Construction.—During construction the tops of the earth walls are carefully protected against rain. During the night and when work was not in progress they were kept covered with a material that would turn the water and prevent its flowing down the surface. Strips of two-ply roofing were used and made excellent material for this purpose. Sisalkraft paper is also very satisfactory for this purpose and is cheaper. The strips were of such lengths that they could be handled by two men, and a light piece of lumber tacked along each edge of the strip helped hold it in place against the wind. When work was delayed so long that the lower section had become dry, the top of the wall was sprinkled with water before starting to build the section above.

An experience in building this poultry house indicates the damage that can be expected from heavy rains when proper protection is not provided. On the day the roof was framed and the roof sheeting was being laid an exceptionally heavy shower of rain came. The roof was in just the right stage of construction to carry the greater part of the water down to the wall but not over the eaves. This caused the water to run down the wall surface at many points where deep grooves were cut. The damage was the greatest around the window frames where considerable repair was required.

Figure 36.—THE SOUTH DAKOTA POULTRY HOUSE BEFORE PAINTING THE WALLS.

The picture of this experimental house was taken just as it was finished and before it was covered. The spots in the walls that were injured by a heavy rain during construction, were easily and quickly repaired with portland cement mortar. When the walls are left bare outside window ledges should be provided with metal strips two inches wide extending below the ledge to force the water to drip from the edge instead of flowing down the face of the earth wall. Protection at the corners is most important. A picture of this house is shown on the cover.

Repair and Retouching of the Walls.—The repair of damaged places in the wall was easily and quickly made and the places were well covered after the walls were painted. In repairing the deep grooves in the wall a few eight penny nails were first driven in the bottom of the grooves, not closer than two or three inches, leaving the heads of the nails to protrude one-half inch. The cavity was then filled with very dry cement mortar which remained entirely firm. As the walls shrink, and the amount of shrinkage will depend upon the amount of sand in the soil used, the joints[26] in the wall will open slightly. These joints were easily and quickly filled with cement mortar. After the forms are removed the bolt holes through the wall are left. These bolt holes were easily filled by tamping them full of the same dirt used in the wall or cement mortar. Cement mortar is advised if the wall is to be left uncovered. A small V-shaped trough about eight inches long and three inches high was used for feeding the dirt into the holes as the tamping was done with a round wooden rod.

The eaves of this rammed earth house are no wider than ordinarily used, having a horizontal projection of 12 inches. A blue print plan, No. 312, for this rammed earth poultry house is available. More complete instructions for building a rammed earth poultry house are given in South Dakota Extension Circular No. 362.

Rammed Earth Blocks for Building Walls

Rammed earth building blocks have been made and laid into walls in the same manner as for clay or cement building blocks. Rammed earth blocks are made from the same kind of dirt as is used for building the monolithic or solid wall. The same test for quality of the dirt is used. A sandy soil that is low in total clay colloids will be favorable. A heavy clay soil will be unfit to use and soils ranging in between these two will be medium in quality. As definitely reported in Experiment Station Bulletin No. 298, medium soils must be protected with a dependable covering. However, trials with walls of rammed earth block indicate that medium soils will stand somewhat better in a block wall than for the monolithic wall providing a resistant mortar is used. When left exposed to the weather the mortar joint seems to retard the weathering action on less favorable soils.

Size and Shape of the Blocks. —The first building blocks of rammed earth were made in 1933. Two small weathering walls were built of these blocks during the summer. In the winter of 1933-34 several hundred of the blocks were made and stored away. In the fall of 1935 a large section of wall (see Fig. 42), in an experimental building, was built of blocks and since that time two inside walls have been built of them. The blocks were made 12 inches wide, by 18 inches long, by 6 inches deep. They weighed 80 lbs. on the average. Half blocks were rammed for corners and openings. These blocks were laid flat in the wall making a 12 inch thickness and each block laid up approximately 120 square inches or seven-eighths of a foot of wall. They were found very heavy to handle in laying, and the size of the form has been changed to make these blocks 15½ inches long (16" with the mortar joint) and with the same width and depth. This length is the same as for

26 See Fig. 32.

most cement blocks that are made today. The blocks could be made in any desired size. The advantage in the larger block is that less mortar is required for laying them in the wall and the fewer mortar joints offer less opportunity for the infiltration of cold air. Thicker walls would be warmer in winter and cooler in summer and if thicker walls of this type were made, an 8 inch by 8 inch by 16½ inch block might be the best size to make and use in building a double wall. The blocks were rammed by hand. They were rammed in three layers and with the same rammers and intensity as for the monolithic wall. Mechanical rammers could of course be used very favorably in their construction. Two special tools working somewhat like ice tongs were designed and used in lifting and handling blocks (see Fig. 41). Green blocks can be handled immediately after being removed from the form but they should be cured for 30 to 60 days before laying into the wall.

Mortar Used for Laying up Wall of Rammed Earth Blocks.—The mortar used for laying up walls of these blocks was dagga plaster (see page 35) plus 10 per cent of Portland cement. A few years ago a report was made of some experimental work that was done by the Bureau of Agricultural Engineering in Washington, D. C. In this study varying amounts of Portland cement were added to soils for mortar and the effects of the admixture were determined. As a result of these findings and knowing the physical characteristics of dagga plaster intimately, we concluded that a mixture of dagga plaster and 10 per cent by volume of Portland cement would make a good mortar. We tried it and it has proved so satisfactory we have used no other up to this time. It bonds with earth even better than common cement mortars and works nicely under the trowel. Its chief merit of course is its low cost.

The complete mixture for this mortar is: two parts of plaster sand, one part of sandy clay, and one-third part of Portland cement. In mixing

Figure 37.—A FORM FOR MAKING BUILDING BLOCKS OF RAMMED EARTH.
This form has a heavy plank bottom and is lined throughout with light galvanized iron. The form is open and this side is dropped down for taking out the blocks. When a concrete floor is available the bottomless form shown in Fig. 38 is handier to use. The blocks in the background are test pieces and were not made in this form.

with shovels the following ratio is used: Six shovels of sand, three shovels of sandy clay, and one shovel of Portland cement.

This same mortar is being tested as a plaster covering for pisé walls and after nearly three years' exposure is in near perfect condition. Striking colors may be secured in this plaster from various colored clays.

Forms for Making Rammed Earth Blocks.—Two different molds or forms were designed and built for making building blocks. Each form had a capacity of four full sized blocks (see Fig. 38). One of these forms was made with a plank bottom while the other is bottomless and must be used on solid concrete floor. The bottomless form was preferred by those who used them. They must be heavily built and easily and quickly released for removing the blocks. They were lined with light galvanized iron as shown in the plan. This eliminates the need for oiling the forms and works satisfactorily. Further improvement is needed in simplifying the bracing and in reducing the time required for releasing the finished blocks. With the present forms the speed of making blocks with two men working at a form is 3 blocks per man hour.

Walls of Block Compared to Monolithic Walls

For rigid climates where the value of a weather proof wall is of great importance the monolithic wall has a decided advantage over the block wall. In longtime durability the monolithic wall will no doubt show a great advantage. Although the mortar dsecribed above has proven very much superior to the mud mortars used in adobe walls in the past, it can hardly be expected to last through a century or more of time, as is claimed for the monolithic walls of early history. The life of most walls of block or brick materials is limited to the life of the mortar joints. From the standpoint of temperature control and for fire proof qualities

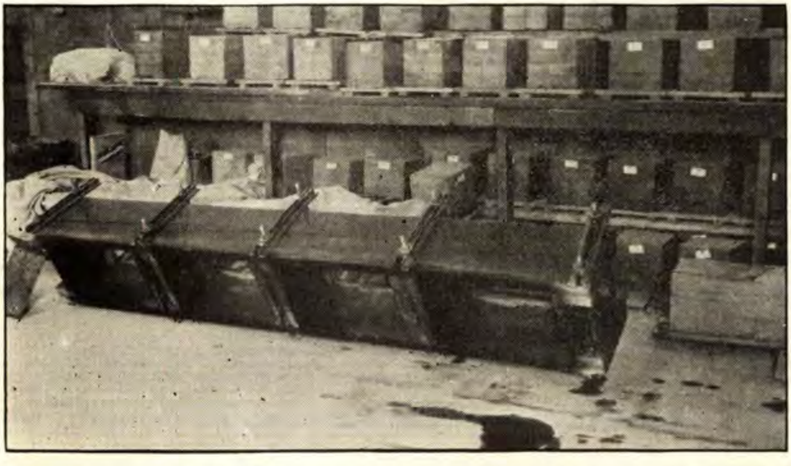

Figure 38.—A FORM WITHOUT A BOTTOM FOR MAKING BUILDING BLOCKS.

This form is tipped up to show that it has no bottom. It is lighter and easier to handle. Only the ends are lined with metal in this form. A detailed plan for making a similar form is shown in Fig. 40.

their advantages would be practically the same. For high walls or high gables the use of blocks would have a decided advantage in construction speed.

For building low walls the construction speed will be considerably in favor of the monolithic rammed earth wall although no tests have been made to obtain accurate comparative figures. The building of the block walls may seem more rapid because the work is divided into two periods of time, the making of the blocks, and the building of the wall. However, the material is handled several times more in building of blocks—the building of the monolithic wall being a "once over, all over process." The new form for making rammed earth blocks will be 9'-8¾" long and provides for making five whole blocks and one-half block at each time it is filled. A detailed plan for building this form is shown in Fig. 40.

Thorough Impregnation of Moisture Through the Soil Adds to the Quality of the Rammed Earth Wall

General observation in building of rammed earth seems to show an advantage in using a dirt that is uniformly moist throughout. When a soil has been allowed to become very dry under the shelter it is difficult to moisten it satisfactorily for immediate use. Experience indicates that a better quality wall will be secured if the moisture is thoroughly and uniformly distributed throughout the soil when it is rammed. Soil that is very dry will contain small hard pieces of dry dirt even after it has been wet down and well mixed. Perhaps the best way to avoid this situation

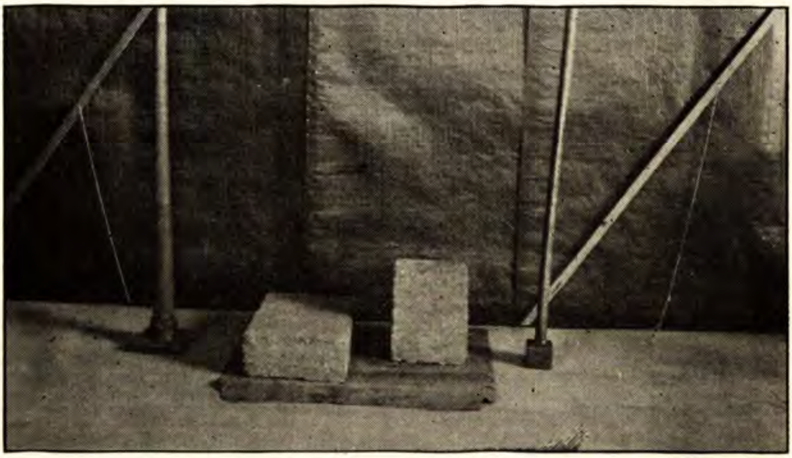

Figure 39.—A FULL SIZED BUILDING BLOCK OF PISE AND A HALF-BLOCK OF THE SAME MATERIAL.

Earth walls made of building block will not be as durable nor as weather proof as the solid walls. They are more convenient to use in building gables. Whole blocks of this size will weigh about 75 lbs. on the average after they have dried out. The common floor rammer on the left is sometimes used for going over the loose layer of dirt in the form for the first time. It is used more in the wall forms than for building blocks.

is to wet down the pile of dirt under the shelter occasionally or to wet down and mix batches of dirt on the mixing board a day or more before it is to be used and pile it up. In this way the moisture will have time to spread through the pile before it is necessary to use it.

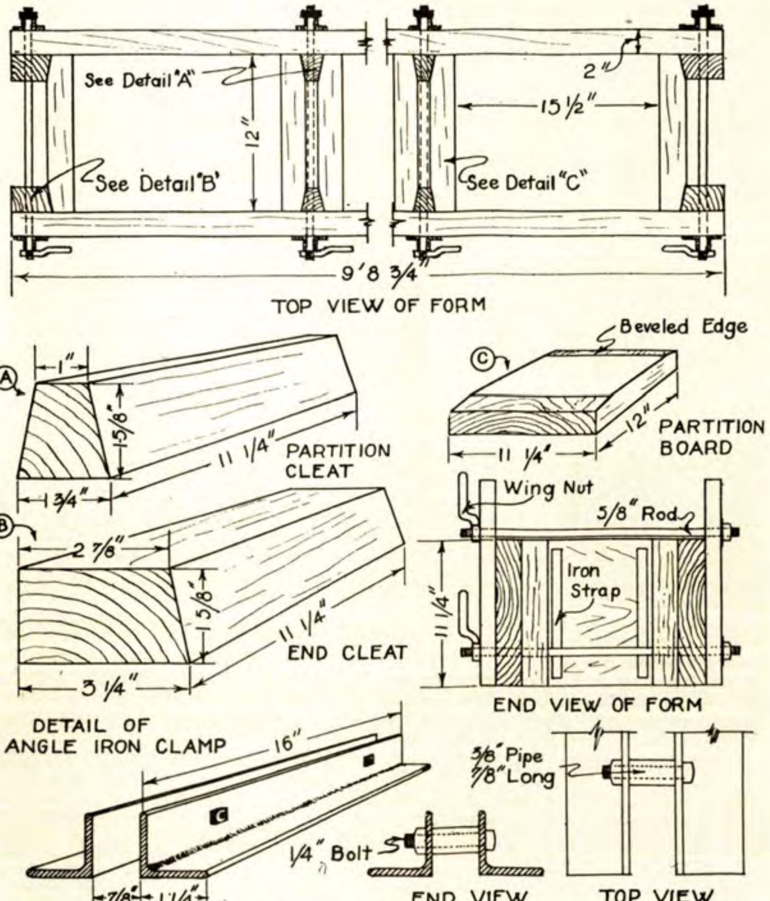

Figure 40.—PLANS FOR MAKING A FORM FOR BUILDING BLOCKS OF RAMMED EARTH.

This form is 9 ft. 8½ in. long over all, and has a capacity of five whole blocks and one-half block. Half blocks will be used in about this ratio in building walls. The whole blocks will be 12 inches by 15½ inches by 6 inches thick.

A Comparison of Earth Building Materials for Compressive Strength When Puddled as a Mud Before Placing, or When Rammed as a Moist Earth

In order to study the strength of earth as a building material, as it is affected by the manner of handling and placing it in the wall, a series of test pieces were made in the laboratory during the second week of September, 1937. Three base soils were used in the study. These are described on page 15 and the sieve analysis for them is given in Table No. 1. No. 1 soil is a black clay soil containing very little sand. Soil No. 2 is a medium sandy clay soil; while soil No. 3 is a very sandy soil containing very little clay. Two methods were compared: The one in which the soil was mixed with water to form a puddled earth and with an admixture of straw, as earth is used in cobb, chalk, and adobe construction; the other in which the soil is only moist and rammed into place as for pisé or rammed earth.

The test pieces were made in a cylindrical steel mold 8 inches in diameter by 16 inches high (see Fig. 43). The test pieces were made in three different depths. These depths were 4 inches, 6 inches and 9 inches and for such slight variations in depth as unavoidably resulted in making them, corrections and the true strength is shown in Col. 10, Table No. 12. The principle reason for using test pieces of different depth was to try out this new mold for testing earth materials and a secondary reason was for checking the results of a former study. Four like pieces of each soil and for each depth and kind were made, making a total of 72 test pieces in all. The soil for the "puddled earth" pieces was taken from the same pile as for the "rammed moist" pieces. The earth was first thoroughly puddled

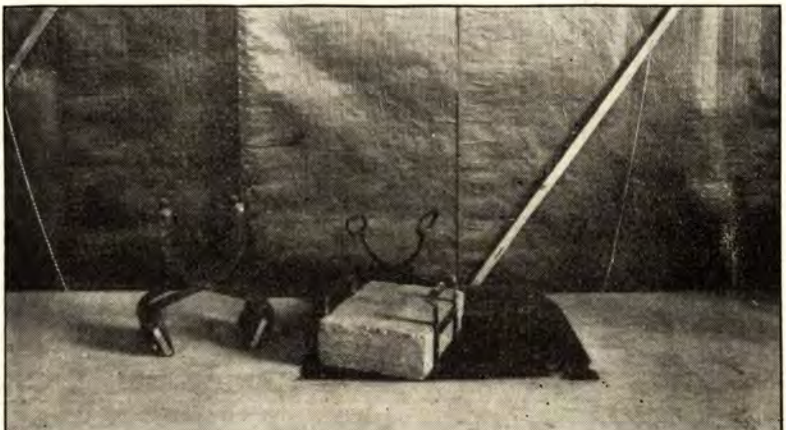

Figure 41.—A PAIR OF TONGS HELPS IN PLACING THE BLOCK IN THE WALL.
A light pair of tongs was found very useful in handling the heavy earth blocks. The flattened tips of the tongs on the block slip under the block rather than into the side, as is the case with ice tongs. The heavy tongs at the left hold the block by means of small nails in the board lips at the bottom. The lighter pair is more popular with the workmen.

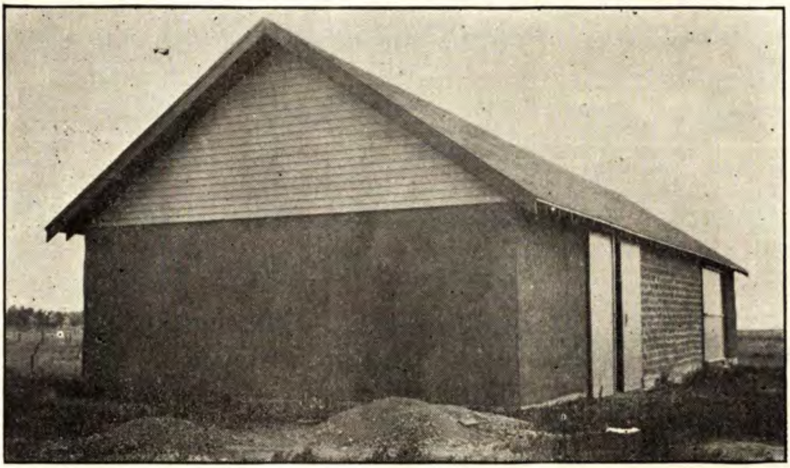

Figure 42.—A MACHINE SHED WITH RAMMED EARTH WALLS AND A SECTION OF WALL BUILT OF BLOCKS.

This building is 26 by 72 feet in size. It contains a section of wall built from blocks. The side and end not showing are covered with paint panels, many of them of transparent paints. This end is covered with dagga plaster and a few narrow panels of plaster are shown at the extreme rear. The roof truss for this building is designed to throw a fairly heavy roof thrust against the walls of this building. The building was two years old when the picture was taken. The gable end of frame construction is not good practice. It should be of a material as durable and as warm as the rest of the wall.

Figure 43.—TEST PICTURES OF "PUDDLED EARTH" AND "RAMMED MOIST" SERIES.

One-third of the test pieces used in the strength study reported in Table No. 12 are shown in this picture. The cylindrical pieces are eight inches in diameter and were made in heights of 4, 6, and 9 inches. The steel mold used in making them and shown in the foreground is 8 by 16 inches.

Table 12.—A Comparison of Strength in Compression of Earth Building Material When Puddled as a Mud and When Rammed as a Moist Earth.

Density when broken. lbs./ft³	1 No. of Like Pieces Tested	2 Weight of Pieces When Made Average of Four	3 Weight of Pieces When Broken Average of Four	4 Loss of Moisture in Pounds Average of Four	5 Loss of Moisture in Per Cent Average of Four	6 Age When Broken	7 Kind of Soil (Base Soils)	8 Puddled Mud or Rammed Moist	9 Ultimate Strength In Compression Average of Four	10 Strength in Lbs. Per Square Inch Corrected for Depth	11 Depth of Pieces (Approximate)
97.63	4	13.62 Lbs.	11.36 Lbs.	2.27	16.6%	6 Mo.	No. 1	Rammed	45,040 Lbs.	896.	4. In.
126.42	4	16.44 Lbs.	14.71 Lbs.	1.73	10.5%	6 Mo.	No. 2	Rammed	50,768 Lbs.	1015.	4. In.
127.71	4	16.06 Lbs.	14.86 Lbs.	1.20	7.5%	6 Mo.	No. 3	Rammed	50,785 Lbs.	1010.	4. In.
117.22 Average							Av.	Rammed	48,864 Lbs.	973.7	4. In.
96.55	4	19.94 Lbs.	16.85 Lbs.	3.09	15.5%	6 Mo.	No. 1	Rammed	34,187 Lbs.	676.	6. In.
124.28	4	24.12 Lbs.	21.69 Lbs.	2.52	10.4%	6 Mo.	No. 2	Rammed	47,180 Lbs.	936.	6. In.
130.24	4	24.80 Lbs.	22.73 Lbs.	2.08	8.4%	6 Mo.	No. 3	Rammed	38,062 Lbs.	757.	6. In.
117.01 Average							Av.	Rammed	39,810 Lbs.	790.	6. In.
96.11	4	30.00 Lbs.	25.16 Lbs.	4.83	16.1%	6 Mo.	No. 1	Rammed	18,000 Lbs.	361.	9. In.
122.77	4	35.80 Lbs.	32.06 Lbs.	3.75	10.5%	6 Mo.	No. 2	Rammed	31,022 Lbs.	617.	9. In.
131.56	4	37.40 Lbs.	34.44 Lbs.	2.94	7.8%	6 Mo.	No. 3	Rammed	25,077 Lbs.	499.	9. In.
116.70 Average							Av.	Rammed	24,699 Lbs.	492.4	9. In.
78.55	4	13.25 Lbs.	9.14 Lbs.	4.11	31.0%	6 Mo.	No. 1	Puddled	17,012 Lbs.	341.	4. In.
107.25	4	15.62 Lbs.	12.48 Lbs.	3.15	20.2%	6 Mo.	No. 2	Puddled	25,252 Lbs.	519.	4. In.
120.83	4	16.25 Lbs.	14.06 Lbs.	2.19	13.5%	6 Mo.	No. 3	Puddled	18,380 Lbs.	369.	4. In.
102.21 Average							Av.	Puddled	20,215 Lbs.	410.	4. In.
76.61	4	18.80 Lbs.	13.37 Lbs.	5.44	28.9%	6 Mo.	No. 1	Puddled	12,375 Lbs.	243.	6. In.
105.66	4	22.37 Lbs.	18.44 Lbs.	3.93	13.2%	6 Mo.	No. 2	Puddled	21,255 Lbs.	428.	6. In.
119.70	4	24.50 Lbs.	20.89 Lbs.	3.61	14.7%	6 Mo.	No. 3	Puddled	14,100 Lbs.	280.	6. In.
100.66 Average							Av.	Puddled	15,910 Lbs.	317.	6. In.
78.31	4	28.75 Lbs.	20.50 Lbs.	8.27	28.7%	6 Mo.	No. 1	Puddled	11,710 Lbs.	233.	9. In.
106.35	4	33.12 Lbs.	27.84 Lbs.	5.28	15.9%	6 Mo.	No. 2	Puddled	15,450 Lbs.	307.	9. In.
115.67	4	34.81 Lbs.	30.28 Lbs.	4.53	13.0%	6 Mo.	No. 3	Puddled	10,657 Lbs.	204.	9. In.
100.11 Average							Av.	Puddled	12,606 Lbs.	248.	9. In.

and mixed with straw in a mortar box. It was then placed in the steel mold and rammed into place with the end of a 2 by 4 inch wood rammer. The moist earth was rammed in the same mold with an 18-pound steel hand rammer and care was used in ramming to see that the pieces were rammed with average intensity. The cylindrical hand rammer shown in Fig. 4 was used. The intention was to ram the test pieces with the average intensity that is used in building rammed earth walls. Earlier study has shown that the strength of rammed earth walls will vary materially with the intensity of ramming as reported in Table No. 7 of this bulletin. As each test piece was taken from the mold it was weighed and measured and placed on a shelf in the research laboratory where the entire series was kept in a temperature of 65 to 70° F. until the time of testing. This period of time covered almost exactly six months. Straw was added to the puddled pieces at the rate of 122 pounds for each 1,000 pounds of earth. This is the amount recommended for adobe brick by Prof. H. C. Schwalen of the University of Arizona who has done experimental work with this type of earth building material.

Av. density rammed earth - 116.98 #/ft³

" " puddled soil - 100.99 #/ft³

Moisture lost in Drying - Rammed — 7.9%

For Non-Pulverized Soils — Puddled — 16.5

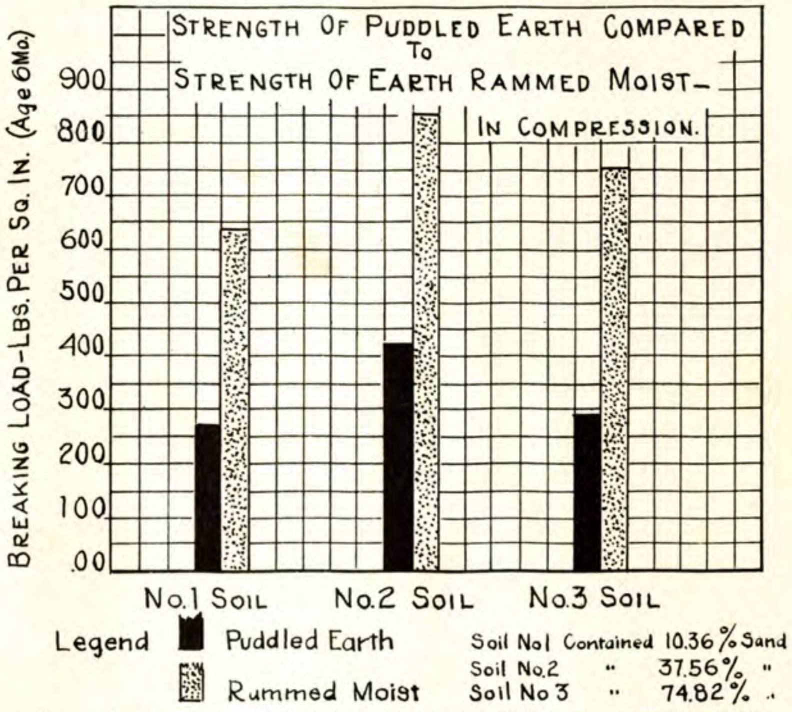

Figure 44.—PUDDLED EARTH WALLS DO NOT HAVE THE STRENGTH OF RAMMED MOIST WALLS.

For all different types of soil and the different depths of test pieces the "puddled earth" showed a compressive strength of 43.2 per cent as great as the "rammed moist" pieces.

The straw was cut in lengths not to exceed six inches because of the relatively small test pieces. The age of these 72 test pieces was just six months when they were broken. They were of course thoroughly air dried containing from one per cent to two and one-half per cent of moisture when broken. The cylindrical test pieces with a diameter of 8 inches furnished a bearing surface of 50.27 square inches on top. Column 9 in Table No. 12 gives the ultimate strength of the cylindrical test piece of this cross-section and Column 10 shows the utlimate strength in pounds per square inch of bearing surface. The depth of the test pieces is shown in Column 11 and the decisive inverse ratio of strength to depth of test piece checks with the former work on this subject as recorded in Table No. 4, page 28. In that test which was made for the purpose of obtaining a correct coefficient for depth of test piece, the No. 3 base soil only was used. The comparison between the two studies must be made in "strength per square inch" for the two tables, since the test pieces were of different size and shape. Another factor enters into the comparison also, due to the difference in age of the test pieces as given in each of the tables.

The results of this study show a decided advantage in the strength of earth material when rammed as a moist earth over the same earth material when puddled as mud. The compressive strength of all "puddled earth" test pieces, including the three different types of soil and the different depths, averaged only 43.2 per cent as great as the "rammed moist" pieces. An interesting ratio is shown between the loss of moisture in the "rammed moist" pieces and the "puddled earth" pieces, as compared to the strength of the two materials. The loss in strength of the puddled material is no doubt largely due to the honeycombed structure of the material after the moisture has left it. A similar loss in strength is found in a concrete structure that is made from a very wet or fluid mixture.

An odd result in this study was the fact that soil No. 1 fell below the other two soils in compressive strength in the rammed earth pieces, whereas, in some former tests it ranked slightly above them. In the age-strength study reported in Experiment Station Bulletin 298, this soil ranked slightly above the No. 2 base soil in compressive strength, and considerably above No. 3 base soil. In this study this soil ranked last in all series except the nine inch pieces of "puddled earth" where it was considerably stronger than the very sandy No. 3 soil pieces. The only explanation for this difference in behavior of the clay soil might be due to the different shaped test piece with less mass and smaller bearing surface.

A Cinder Admixture Study

A study is underway to determine the effect of adding soft coal cinders to soils that are low in sand and somewhat high in clay colloids. As shown in Experiment Station Bulletin 298, the addition of sand to soils that are low in sand content improves the quality of the soil and the resistance of the rammed earth wall to weathering. Sandy soil also rams solid more quickly. A series of test pieces were made using base soils No. 1 and No. 2. Both of these soils are improved by an addition of sand. To these soils equal amounts of sand and cinders have been added to two series of test pieces which together with the check pieces will be broken at a later date. This is for comparing the effect of cinders and sand as an admixture, upon the strength and physical structure of the rammed earth pieces. To-date two small weathering walls have been built using cinders as an admixture. In one of these walls one part of cinders by volume, to two parts of No. 2 base soil was used. In the other wall two parts of cinders were used to one part of the same soil. These walls were built for the purpose of com-

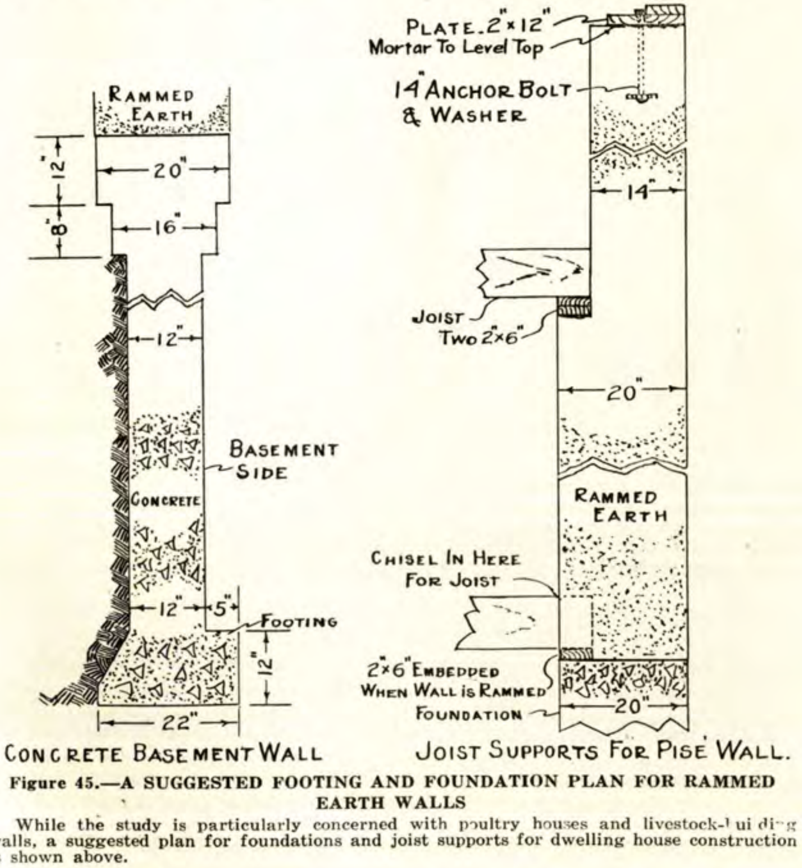

Figure 45.—A SUGGESTED FOOTING AND FOUNDATION PLAN FOR RAMMED EARTH WALLS

While the study is particularly concerned with poultry houses and livestock-building walls, a suggested plan for foundations and joist supports for dwelling house construction is shown above.

paring their weather resistance. We already have check walls of this soil in the yard which will be satisfactory for comparison.

Two conclusions have been drawn from the making of the test pieces. The cinders which contained a considerable amount of hard burned clinkers definitely increases the transverse strength of the material. A second conclusion was evident from ramming the mixtures. The cinders caused the mixture to ram slightly quicker but not quite as solid as the sand admixture. The cinders used were from eastern mine-run coal burned under boilers in a power plant. A portion of the fine ash was screened out of the cinders used in this test, as the percentage of fine ash seemed to be higher than average. The sieve analysis of the cinders used showed 79.5 per cent retained on a one-fourth inch screen, 7.5 per cent retained on a one-eighth or No. 8 screen, 9.4 per cent were retained on a No. 50 screen, and 3.83 per cent passed through the No. 50 screen.

Figure 46.—A RAMMED EARTH GARAGE WITH FLAT ROOF.

This double garage has rammed earth walls and a flat roof.The walls are stuccoed. The building was built in 1935 by Col. Paul S. Bliss on his western ranch at Hettinger, N. D. Col. Bliss later built a ranch home of similar design.

A Few Brief Building Specifications

Sandy clay or sandy loam soils are most favorable of all soils for pisé or rammed earth walls. Heavy clay soils are unfit for use. Soils containing 18 to 24 per cent total clay colloids may be expected to stand for many years as a bare earth wall. Soils containing 24 to 39 per cent total clay colloids are medium soils. They will be perfectly satisfactory for rammed earth walls but will eventually require a protective covering for the exterior surface. All of these soils will be improved by the addition of sand and many will be improved to a point where they will stand as bare earth walls.

The minimum thickness for any rammed earth wall should be 12 inches. The thickness should never be less than one and one-half inches for each foot of wall height. For dwelling houses the minimum thickness for the lower wall should be 18 inches and 20 or 22 inches is not too great for large two-story dwellings.

Footings for the concrete foundation for earth walls should be ample for carrying a heavy load. They should vary in width from one and one-fourth to one and one-half times the thickness of the wall, depending upon the height of the wall and the bearing strength of the soil.

The top of the foundation must be of the same width as the thickness of the wall. This full thickness must extend for a distance of one-half the thickness of the wall below the top, when the special type foundation is used. Plank plates should be anchored to the earth wall by bolts that are embedded in the wall to a depth equal to the thickness of the wall at the plate. The bolt should carry an anchor washer or plate one-fourth inch thick and one square inch in area for each inch in thickness of the wall.

Sills or plates for carrying joists on a rammed earth wall may be of plank or of concrete. In no case should the ends of the joists rest directly

Figure 47.—A DWELLING HOUSE WITH PISE' WALLS AND THATCHED ROOF.
This house with a typical English thatched roof was built in Toronto, Canada in 1937 by Blair A. Burrows, 120 Bedford Road.

on the earth wall. For normal floor loads the ledge for carrying the plate and joist ends should be not less than six inches (see Fig. 45). It is comparatively easy to embed either a plank or concrete plate for this purpose within the form as the wall is rammed.

"Pre-cast tile beam floor" lends itself well to fire proof construction in rammed earth structures. They may be used for flat roof construction as well as for floors.

Rammed earth blocks lend themselves to partition construction where fireproofing is important. Twelve inch partitions will be satisfactory for dwelling house construction. Ordinary frame partition construction can be used very satisfactorily in rammed earth buildings. The great advantage of this material is in the outside walls where its insulating value is most effective.

Rammed earth or pisé walls are excellent in insulating quality, during construction in drying weather. If delay is necessary they must be covered from the sun. Unattached wall sections of this material, in thin walls at least, may warp out of line due to unequal drying out of the moisture. One twelve inch wall section left standing throughout the summer was pulled out of line at the top by two or three inches in a length of 40 feet. The tops of unfinished walls must be protected against rain at all times during construction. Fig. 34 shows methods of tacking tough building paper over the top of the walls for this purpose. The lower edges of this paper must be held away from the wall to direct the flowing water away from the wall face. No trouble is experienced from flowing water after the roof is on, except around the window ledge on the outside of the windows. Water will flow back under a horizontal window ledge and damage the face of the wall. The ledge must be made to shed the water from the outer edge. The galvanized-iron strip shown in Fig. 26 is for this purpose.

When very dry dirt is being used for building, the dry clods should be screened out and the moisture mixed with the dry dirt some time before the dirt is used. This gives the moisture time to spread through the dry particles. The period of standing in the pile should not be less than overnight, and a longer period is better.

Summary

Rammed earth or pisé walls are excellent in insulating quality, making an exceedingly warm wall in cold weather and a cool wall in hot summer. They should be made thick for the greatest benefits, as their insulating quality increases directly with the thickness of the earth wall. In addition to being a good insulator, rammed earth walls are extremely stable. They are also fire proof, durable, and weather proof. Rammed earth is probably the most nearly weather proof of any wall material used today having insulating qualities, and due to this fact, it lends itself well to modern air conditioning. However, the purpose of the Experiment Station in studying this material for wall construction was not for dwelling house construction but for the benefit of the poultryman and stockman. Thick, weather proof walls of earth can hardly be equalled in a rigid climate. They not only maintain uniform temperatures but they absorb moisture from a too moist air and give it back when the air becomes too dry.

Rammed earth walls are not temporary walls in any sense. They are the most permanent of walls. They are not important because of their low cost, but because of their high value. They are somewhat tedious to build and when the wall is finished the rest of the building should be well built and tightly fitted so that the value of the insulated walls will not be lost. Perhaps the most valuable use of these walls is for the poultry house, the construction of which is outlined in Extension Circular 362. The poultry house shown on the cover of this bulletin finally averaged, in a three year temperature study, 5.9° F. warmer in early morning than a well built frame house of the same size, dimensions and design. This was for the five coldest months of the year. A farm owner with a good flock of laying birds could well afford to spend three or four weeks in the early fall building a rammed earth poultry house for them.

The speed of building the solid rammed earth wall will vary from 1½ to 2 cubic feet of wall per man hour depending upon the experience of the crew in planning the work and changing the forms. Mechanical rammers driven by compressed air may average as high as 7 cubic feet per hour.

A sandy and comparatively light sandy soil is a favorable soil for building earth walls and a heavy clay soil is unfit to use. An average or medium quality soil will not stand satisfactorily as a bare wall but must be protected with a covering of some material.

It is the sand in the wall that resists the driving rains. Up to the present time no entirely dependable covering except plasters have been proven, although ordinary good quality linseed oil paints have been found satisfactory on very sandy earth walls. It was hoped that a transparent paint covering could be found that was dependable but no such paint has been proven as yet. The reason for the desirability of the transparent paint is to preserve the identity of the material in the wall and at the same time to protect it during the green stage.

Screening the dirt for rammed earth construction is necessary only when dry clods are found in it or when it contains undesirable trash. It is difficult to moisten the dry clods to their center for ramming and therefore best to screen them out.

Deep concrete foundations are unnecessary for low rammed earth walls, although the foundation should extend 24 to 30 inches below grade, depending upon the soil and drainage for that location. The foundation should be strong, with a good wide footing, as wide as the wall at the top, and should extend at least 12 inches above grade. For dwelling house and larger buildings with high walls the foundation should go below the frost line.

Fibrous materials such as grass, fine roots and straw increase the strength of pisé in compression, but are unnecessary for this reason as the strength of the material is more than ample when proper thickness for the height of wall are used.

Adding Portland cement to very sandy soils and especially fine sandy soils decidedly increases the strength. Adding cement to soils low in sand increases the strength very little, if any.

Adding hydrated lime to the soil reduced the strength materially and made the material crumbly.

Steel reinforcing rods with rough surface were the best reinforcing material that was tried for rammed earth construction. Steel rods or plank may be used over narrower openings, but reinforced concrete lintels are advised for wide openings in pisé walls.

Window ledges should be made to direct the flow of water directly from their outer edge to the ground. Ordinary window ledges will carry the flow of water back underneath to the surface of the wall. The only trouble experienced with pisé walls from driving rains was at this point where even the best walls were damaged.

Rammed earth block walls will not be as weather proof as the solid wall. The blocks in the wall are fully as resistant to weather. Building with pisé blocks may be more convenient for some who like to divide the building time into the two periods: making the blocks, and laying them in the wall. Building the solid wall is a "once over, all over" method and the total building time will be less for this type. Rammed earth blocks are more convenient to use in high work such as the high gable ends of a building.

An experienced crew will build a monolithic rammed earth wall in slightly less time than is required for them to make adobe brick and then lay them into a wall.

Moisture Losses - Table #12 P. 70
Inside -

Rammed Blocks Lost: Average -

Soil #1 - - - — 16.066 %
Soil #2 - — - - 10.466 %
Soil #3 . - - - - 7.900 %

Av. Of. Rammed - — 11.477 %

Puddled Blocks Lost: Average

No. 1 soil - - - — - 29.533 %
No. 2 " - - - — 16.433 %
No 3 " - - - - 13.743 %

Av. Of Puddled 19.9 %

Save this!