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BUILDING MATERIALS AND STRUCTURES

REPORT BMS96

Properties of a Porous Concrete of Cement and Uniform-Sized Gravel

by

Perry H. Petersen

NATIONAL BUREAU OF STANDARDS

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Properties of a Porous Concrete of Cement and Uniform-Sized Gravel

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PERRY H. PETERSEN

ISSUED MARCH 18, 1943

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

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Foreword

This report describes an investigation of physical properties of a porous concrete of cement and uniform-sized gravel, undertaken in cooperation with the Federal Public Housing Authority to determine the application of such a concrete in the construction of low-cost housing.

The technical facts presented provide data from which architects and engineers can determine whether performance requirements are met.

Lyman J. Briggs, *Director.*

Properties of a Porous Concrete of Cement and Uniform-Sized Gravel

by PERRY H. PETERSEN

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ABSTRACT

The physical properties of a porous concrete consisting solely of portland cement, water, and uniform-sized gravel were investigated. Each of three coarse aggregates, grits (No. 8 to No. 4), pea gravel (No. 4 to ⅜ inch), and ¾-inch gravel (⅜ to ¾ inch), was used, with 2½ bags of cement per cubic yard in concrete tamped in place and 3 bags per cubic yard when no compacting was done. Walls, wallettes, beams, and bond pull-out specimens were tested, as well as 6- by 12-inch control cylinders. Compressive, transverse, shearing, and bond strengths are reported, as well as resistance to heat transfer, water penetration by capillarity, and rain penetration.

I. INTRODUCTION

Plain or with reinforcement, concrete is readily adaptable to most structures, the strength requirements being attained by the correct proportioning of the ingredients and the use of proper workmanship. There is being brought to the attention of the building industry at this time a type of porous concrete made solely of cement, gravel, and water, the gravel being of a uniform size. Since sand and other size gravels are excluded in the proportioning of the ingredients and the cement content is kept down to about half that of the usual structural concrete, a highly porous material is obtained. Certain promising features of such a material were believed to warrant an examination of its physical properties. In some localities, there is an abundance of uniform-sized gravel compared with the supply of the graded aggregates used in regular concrete. Since no excess water is used, bleeding is eliminated and hydrostatic pressures do not exist, thereby allowing a rougher type of formwork.

This report deals with a porous concrete such as is obtained when using each of three different-sized aggregates. The methods of mixing and placing that were used are outlined, together with the various tests performed. The specimens were tested structurally for compressive, transverse, bond strength, and shear properties, as well as heat transfer, water capillarity, and resistance to rain penetration.

II. MATERIALS

1. Cement

The cement used was North American brand portland cement.

2. Aggregate

The aggregate was Potomac River gravel of three different sizes, namely, grits, pea gravel, and a ¾-in. gravel. The grits and pea gravel were obtained commercially as such, but the ¾-in. gravel was screened at the Bureau from commercial ¾-in. gravel. The sieve analyses are given in table 1. The absorption, apparent specific gravity, and the bulk specific gravity on a surface dry basis are given in table 2.

Table 1.—*Sieve analyses of aggregates*

U. S. Standard Sieve	Percentage, passing, by dry weight								Fineness modulus
	1 in.	¾ in.	½ in.	⅜ in.	No. 4	No. 8	No. 16	No. 30	
Grits				100	91	27	5	2	4.8
Pea gravel			100	98	25	2	1	0	5.7
¾-in. gravel	100	96	31	2	0				7.0

Table 2.—*Data on ingredients and mixtures*

	Grits		Pea gravel		¾-in. gravel	
Absorption, percentage by dry weight [a]	0.6		0.7		0.6	
Bulk specific gravity, surface dry basis [a]	2.63		2.56		2.61	
Apparent specific gravity [a]	2.66		2.61		2.64	
Sieve analyses limits (approx.)	No. 8 to No. 4		No. 4 to ⅜ in.		⅜ in. to ¾ in.	
Cement content ... bags per cu yd	3.02	2.45	2.95	2.51	3.16	2.51
Method of placing	Loose	Tamped	Loose	Tamped	Loose	Tamped
Dry aggregate per bag of cement ... lb	736	1,075	750	1,085	770	1,100
Water-cement ratio by weight	0.50	0.50	0.50	0.50	0.40	0.44
Weight of fresh concrete ... lb/ft³	98.2	110.3	97.1	113.9	105.5	114.9

[a] Determined according to the ASTM Standard Test Method C 127–39.

III. PRELIMINARY STUDIES

A preliminary investigation was conducted to develop techniques in mixing and placing the porous concrete and molding representative cylinders, and to obtain approximate values of compressive and transverse strengths.

1. Mixing the Porous Concrete

A rotary drum-type mixer was used and found satisfactory, although the paddle type is recommended by some investigators. In charging the mixer, part of the required water was put in first, followed about 15 seconds later by the gravel and cement. By this procedure, each batch gained some cement adhering to the inside of the mixer from the previous batch, but lost about the same amount to the following one. Care was taken to add just enough water during the mixing to produce a sheen to the cement coating on each particle of gravel so that, wherever any two particles touched, a meniscus of cement slurry was formed of considerably greater area than the actual contact surfaces. The total mixing time was kept between 2½ and 3 minutes.

2. Placing Concrete in Wall Specimens

Two methods of placing the porous concrete were used, namely, the *loose* and the *tamped*. The designation *loose* signifies that the concrete was poured into the forms and allowed to settle in place without any tamping, rodding, or other compacting. The designation *tamped* signifies that the concrete was compacted in place with wood tampers of end dimensions 2½ by 4 in.

A trial wall, 100 in. high, 56 in. long, and 3 in. thick, was made, using grits as the aggregate. The concrete in the lower half was tamped in place and in the upper half placed loose. No difficulty was experienced in placing the concrete by either method in a wall of this thickness. Upon stripping the forms, the surface texture of both halves was similar to that shown for grits in figure 1.

Figure 1 illustrates the difference in texture of the walls made with the three aggregates, the concrete in the specimen on the left in each group having been tamped, and that on the right having been placed in the loose condition. It is to be noted that a surface finish such as plaster, stucco, or a grout is required for this type of concrete, in order to prevent unraveling of the aggregate at the surface when the walls are subjected to any abuse.

3. Method of Molding Cylinders

Cylinders were molded in two different ways to correspond to the method used in placing the concrete in the wall specimens. For the loose condition, cylinders were made by dribbling the fresh concrete from a scoop against the inside face of the mold in small quantities and the top finished off with a trowel, compacting about a 2-in. mound of excess material into the cylinder. Tamped cylinders were made by tamping the concrete 25 times in each of 3 layers, using a length of pipe with a cap of 2-in. outside diameter, the whole weighing about 5 lb.

4. Preliminary Tests, Using Grits

Small walls or wallettes, 6 in. thick, 30 in. high, and 30 in. wide were made of grits with cement contents of 2½ and 4 bags per cu yd, each in the tamped and in the loose condition. The compressive tests of the wallettes, load applied to the top (6 by 30 in.), were made at the age of 7 and 28 days, and the transverse tests were made at 7 days with the walls in a horizontal position, centrally loaded on a span of 24 in. The compressive strengths are shown in figure 2. Two sets of cylinders were molded from the batches for each compressive-test wallette, one set placed loose, and one tamped, regardless of whether the concrete for the wallette was tamped or placed loose. Thus, cylinder strengths are also shown for two other cement contents, the cement content being computed from the actual weight of the cylinders upon stripping the molds 24 hr after molding.

The moduli of rupture of the wallettes at 7

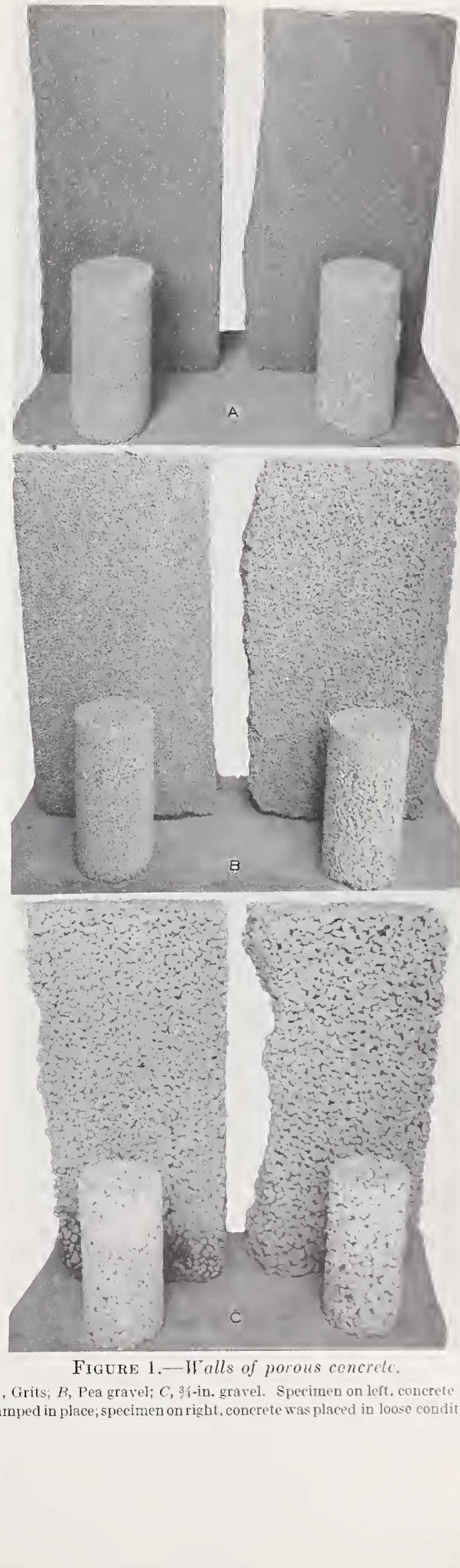

Figure 1.—*Walls of porous concrete.*

A, Grits; *B*, Pea gravel; *C*, ¾-in. gravel. Specimen on left, concrete was tamped in place; specimen on right, concrete was placed in loose condition.

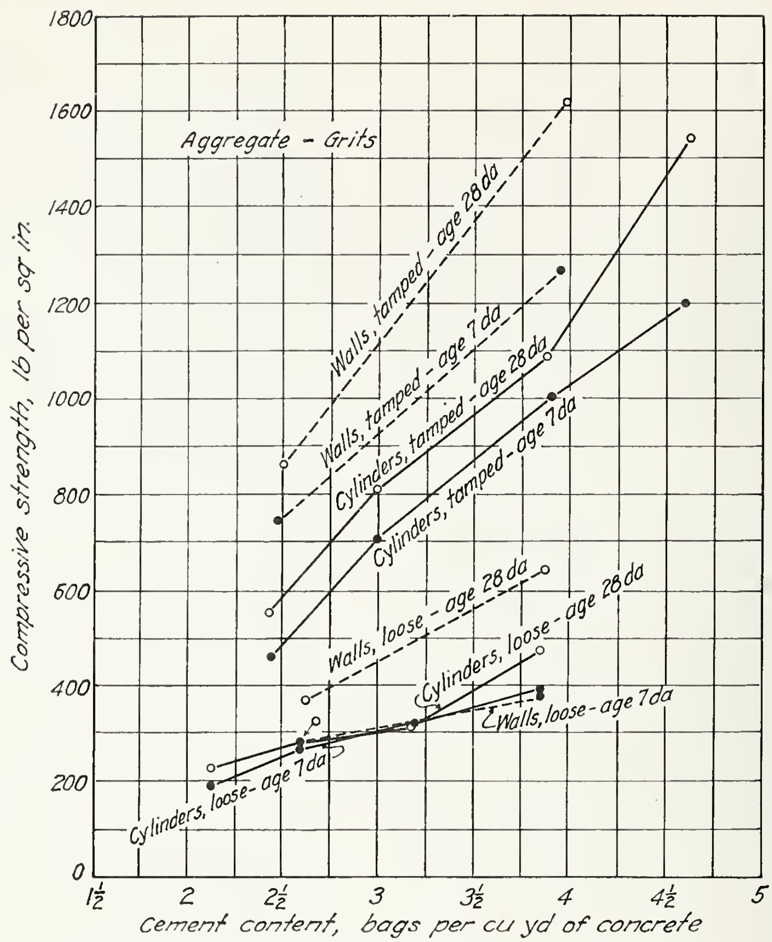

FIGURE 2. —*Compressive strength of porous concrete, using grits.*

days were, respectively, 44 and 73 lb/in.^{2} for the 2½- and 4-bag mixes placed loose, and 78 and 178 lb/in.^{2} for the 2½- and 4-bag mixes tamped in place.

5. Preliminary Tests, Using Pea Gravel

The same two mixes of 2½ and 4 bags of cement per cu yd, placed loose and tamped, using pea gravel, were used in the 7-day compressive tests, and the transverse tests were made at 7 days for both the 2½- and 4-bag mixes placed loose. Three cylinders loose and three tamped were made along with each wallette, whether or not the concrete in the wallette was placed loose or tamped. The compressive strengths of the wallettes and cylinders are shown in figure 3. The moduli of rupture at 7 days were, respectively, 39 and 72 lb/in.^{2} for the 2½- and 4-bag mixes placed loose.

6. Preliminary Tests, Using ¾-in. Gravel

Tests were also made with the ¾-in. gravel in the same way as was done with the pea gravel. The compressive test results of wallettes and cylinders are shown in figure 4. The moduli of rupture at 7 days were, respectively, 61 and 98 lb/in.^{2} for the 2½- and 4-bag mixes placed loose.

IV. DESCRIPTION OF SPECIMENS AND TEST RESULTS

In these tests, each of the three aggregates was used with a cement content of 3 bags per cu yd in concrete placed loose, and 2½ bags per cu yd tamped in place. Records were kept of batch weights, amounts of water, and weights per cubic foot of wet concrete; the latter was determined with a standard cubic-foot measure. These data are shown in table 2.

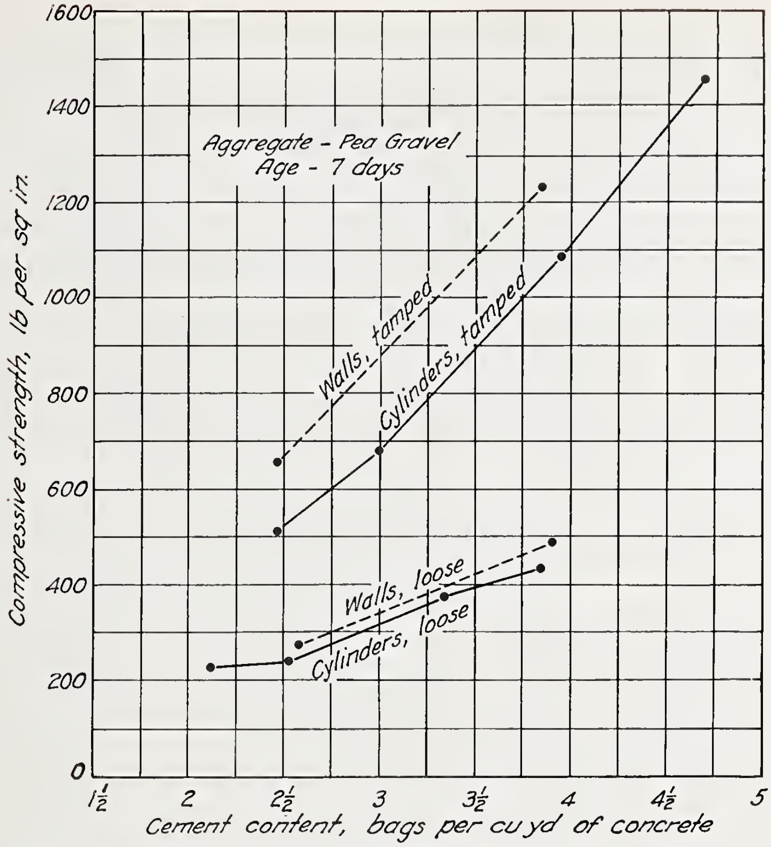

Figure 3.—*Compressive strength of porous concrete, using pea gravel.*

All the walls were 6 in. thick, and the test cylinders were of the standard 6- by 12-in. size. The forms were made of ⅝-in. plywood, with 2- by 4-in. studs, 4- by 4-in. wales, and 2- by 6-in. end forms. To facilitate handling, all the walls were built on steel channels.

1. Transverse Strength

The wallettes for transverse tests were 6 by 30 by 30 in., as in the preliminary tests, and four of each mixture were made. Two wallettes were monolithic and two had horizontal transverse joints at midheight, the top half being poured 24 hr after the bottom half, without any grouting or extra preparation of the bonding surfaces. These wallettes were left without a surface finish and were tested at 28 days, together with their respective cylinders. The moduli of rupture are given in table 3, together with the compressive strength of the cylinders. Shown in figure 5 is the ¾-in.-gravel wallette, concrete placed loose, with a cement content of 3 bags of cement. The wallette lies horizontally for the transverse test on a span of 24 in. between rollers; the load being applied along the center line.

Table 3.—*Moduli of rupture of walls and compressive strength of cylinders of porous concretes*

Aggregate	Grits		Pea gravel		¾-in. gravel	
Normal cement content, bags per cu. yd.[a]	3	2½	3	2½	3	2½
Method of placing	Loose	Tamped	Loose	Tamped	Loose	Tamped
Modulus of rupture of monolithic walls, lb/in.²	96	135	82	96	85	101
Compressive strength of cylinders, lb/in.²	410	590	410	700	580	930
Modulus of rupture of transverse joint walls, lb/in.²	38	22	39	26	54	(b)
Compressive strength of cylinders, lb/in.²	410	600	390	720	580	(b)

[a] See table 2 for actual cement content.
[b] Transverse-joint walls not made.

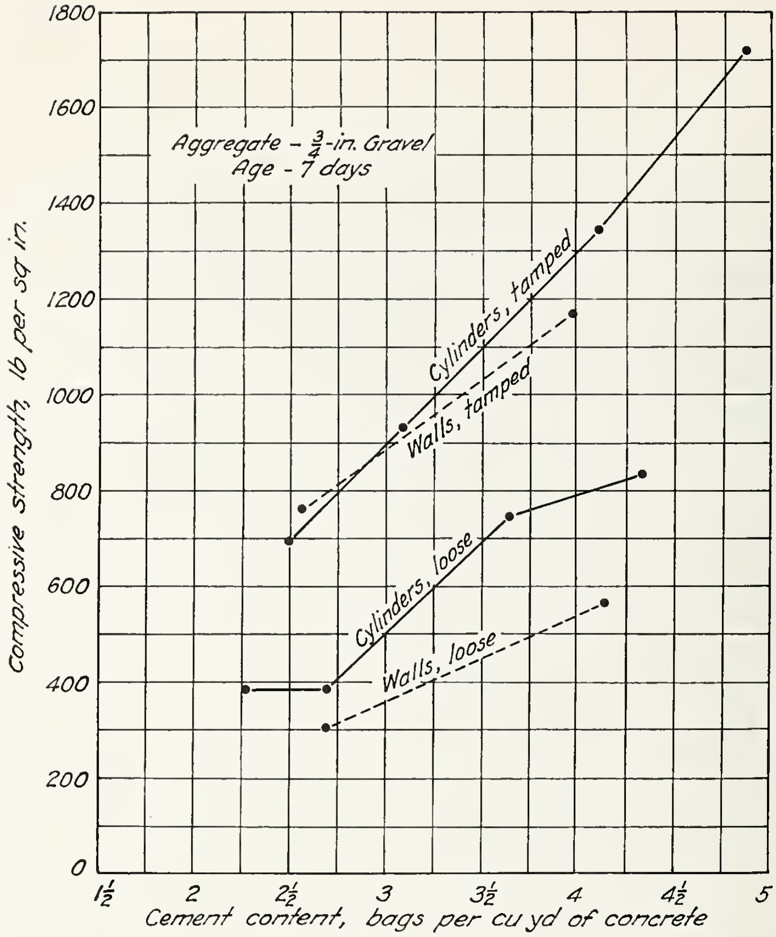

FIGURE 4.—*Compressive strength of porous concrete, using ¾-in. gravel.*

2. Heat-Transfer Properties

(a) *Specimens*

One wall of each mixture was made for the heat-transfer tests, the walls being 100 in. high, 6 in. thick, and 56 in. wide. As the walls were highly porous and offered little resistance to the transmission of air, they were finished, 2 weeks after pouring them, with a ⅛-in. coating of stucco on the weather face and two coats of cement-water paint on the edges, top, and other face.

The stucco was proportioned 1:0.2:3.0 by dry weight of North American brand portland cement, Miracle brand hydrated lime, and Potomac River building sand. It was troweled on to about ⅛-in. thickness and, after the preliminary set had taken place, was brushed with a wet whitewash brush to eliminate the trowel marks.

The cement-water paint was applied in two coats, 24 hr apart, the first being in the proportions of 1:0.25:1.0 by dry weight of white portland cement, Miracle brand hydrated lime, and Potomac River building sand passing a No. 30 sieve. The finish coat was 1:0.25 of white portland cement and hydrated lime. Both coats of cement-water paint were applied to the walls made of grits and pea gravel, using a roofers brush. However, on the ¾-in.-gravel walls, a fender brush was used for the first coat and the roofers brush for the second coat.

The approximate quantities of the materials for surface finishes used on each wall are given in table 4. These values may vary with any slight increase or decrease in the thickness of the stucco or with any change in consistency or brushing technique in applying the cement-water paint.

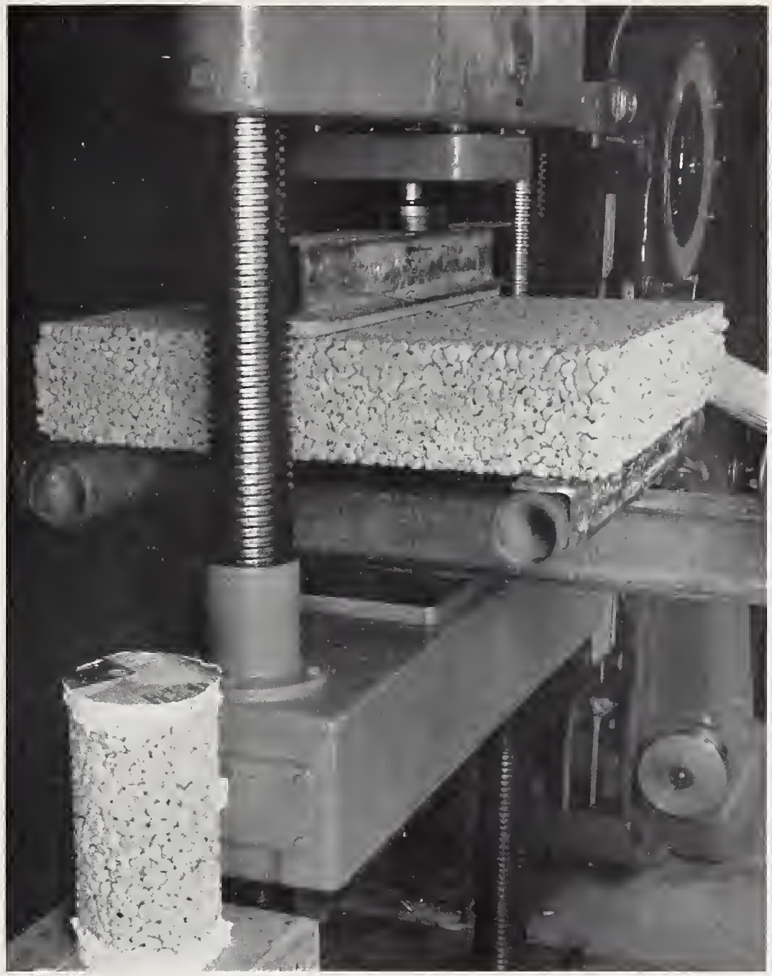

FIGURE 5.—*Transverse test.*

(b) *Test Equipment and Procedure*

The heat-transfer tests were conducted in the shielded hot-box apparatus by the Heat Transfer Section at this Bureau. During the test, heat flowed from the metering and shield boxes, which were heated electrically, through the wall to the cold box, which was cooled by a refrigerating machine. The electric energy supplied to the metering box and measured by

TABLE 4.—*Quantities of materials used for wall-surface finishes*

Aggregate	Grits		Pea gravel		¾-in. gravel	
Nominal cement content, bags per cu yd [a]	3	2½	3	2½	3	2½
Method of placing	Loose	Tamped	Loose	Tamped	Loose	Tamped
Stucco materials:						
Cement, lb/ft²	0.53	0.53	0.59	0.53	0.80	0.64
Hydrated lime, lb/ft²	.11	.11	.12	.11	.16	.13
Sand, lb/ft²	1.59	1.59	1.76	1.59	2.40	1.91
Cement-water paint materials:						
First coat:						
Cement, lb/ft²	(b)	(b)	.29	.20	.46	.33
Hydrated lime, lb/ft²	(b)	(b)	.07	.05	.12	.08
Sand, lb/ft²	(b)	(b)	.29	.20	.46	.33
Second coat:						
Cement, lb/ft²	(b)	(b)	.10	.07	.12	.12
Hydrated lime, lb/ft²	(b)	(b)	.03	.02	.03	.03

[a] See table 2 for actual cement content.
[b] Quantities were not obtained.

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a watthour meter was taken as closely equivalent to the heat energy transferred through the area of the specimen covered by the metering box. The temperatures in the metering and in the shield boxes were the same and kept at 70° ±0.5° F, whereas that in the cold box was at 0° ±0.5° F. The stucco face, designated as the weather side of the wall, was turned against the cold box, and the cement-water paint surface was used at the hot-box side.

(c) *Heat-Transfer Data and Results*

The results of the observations on heat transfer are given in table 5, the heat transmission of the specimens being expressed in three ways. Two include the effect of surface coefficients, and a third is independent of them. The first result, the observed thermal transmittance, u, is the number of Btu per hour transmitted through each square foot of specimen for each degree Fahrenheit temperature difference of the air on opposite sides of the walls. This value includes the observed surface coefficients, fi and fo, as shown in the table. The second value for thermal transmittance, shown as U, is corrected to agree with the conditions recommended in the ASHVE "Guide" for 15 mph wind outside and zero wind inside, using surface coefficients of 1.65 and 6.00 for fi and fo, respectively. The third value, C, the thermal conductance, represents the number of Btu per hour transmitted through each square foot of specimen for each degree Fahrenheit temperature difference between the surfaces of the two sides of the wall and is therefore independent of the surface coefficients. The thermal conductivity, k, is equivalent to the conductance of the material per inch of thickness.

Table 5.—*Heat-transfer coefficients* [a]

Aggregate	Grits		Pea gravel		¾-in. gravel	
Nominal cement content, bags per cu. yd.[b]	3	2½	3	2½	3	2½
Method of placing	Loose	Tamped	Loose	Tamped	Loose	Tamped
Weight, lb./ft.³	98.2	110.3	97.1	113.9	105.5	114.9
Thickness, in.	6.0	6.0	6.0	6.0	6.0	6.0
Observed thermal transmittance, u [c]	0.551	0.561	0.520	0.590	0.618	0.671
Corrected thermal transmittance, U	.680	.702	.643	.751	.786	.874
Thermal conductance, C	1.43	1.54	1.28	1.79	2.00	2.69
Warm surface film conductance, fi	1.90	1.89	1.88	1.87	1.87	1.91
Cold surface film conductance, fo	1.70	1.66	1.64	1.66	1.71	1.68
Thermal conductivity, k	8.6	9.2	7.7	10.7	12.0	16.1

[a] Determined by shielded hot-box apparatus. Cold side of wall finished with ⅛-in. stucco. Warm side of wall finished with 2 coats of cement-water paint.

[b] See table 2 for actual cement content.

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

u=number of Btu per hour transmitted through each square foot of specimen for each degree Fahrenheit difference in temperature between the air on the 2 sides, as observed under test conditions.

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

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

k=The thermal conductivity of the material, equivalent to the conductance per inch of thickness.

3. Compressive Strength

Compressive tests at an age of 7 weeks were made with wall specimens of two sizes. The walls which had been previously tested for heat-transfer properties at 4 weeks were used as one of the compression specimens. A wallette was also tested in compression at the same age, this specimen having been made and the surface finished like the larger wall and at the same time.

Shown in figure 6 is the wall made of ¾-in. gravel, using 3 bags of cement, the concrete placed in the loose condition. During the compressive test, deformation readings were taken with a 20-in. Whittemore strain gage on three vertical lines, on each face of the wall, for uniform increments of load. The average secant modulus of elasticity at an applied stress of 200 lb./in.² is given in table 6, together with the maximum compressive strengths of walls and cylinders. The dispersions of the strength values of the individual cylinders from the mean were greater than is usual with workable dense concretes.

Figure 7 shows the 30-in. wallette set up for compressive test. The face shown is stuccoed, ans the edge and back face are cement-water painted. The top and bottom were capped previous to the test with a Lumnite cement mortar.

FIGURE 6.—*Compression test of 100 by 56 by 6 in. wall*

4. Shrinkage and Thermal-expansion Coefficients

For determining the amount of shrinkage and the coefficients of thermal expansion, one 30-in. wallette was built for each mixture. On both faces, there were four 20-in. gage lines, two horizontal and two vertical, each 5 in. from the edges of the walls. Observations were made approximately once a week with a Whittemore strain gage. The specimens were allowed to remain in the laboratory, where neither temperature nor humidity was controlled. After they had aged at least 3 months, they were stored in a drying room, kept at 95° to 100° F, and after drying them, a set of observations was taken. Then, they were

TABLE 6.—*Compressive strength and secant modulus of elasticity*

Aggregate	Grits		Pea gravel		¾-in. gravel	
Nominal cement content, bags per cu. yd.[a]	3	2½	3	2½	3	2½
Method of placing	Loose	Tamped	Loose	Tamped	Loose	Tamped
Compressive strength:						
Walls 56 by 100 by 6 in., lb/in^2	647	665	504	667	621	835
Cylinders, lb/in^2	491	582	447	645	520	930
Wallette 30 by 30 by 6 in., lb/in^2	714	995	551	918	808	1,090
Cylinders, lb/in^2	469	626	380	654	700	947
Secant modulus of elasticity at 200 lb/in^2:						
Wall 56 by 100 by 6 in., lb/in^2	1,010,000	1,130,000	830,000	1,210,000	1,670,000	2,080,000

[a] See table 2 for actual cement content.

FIGURE 7.—*Compression test of 30- by 30- by 6-in. wallette.*

transferred to a cold room with a temperature between 8° and 12° F and, when the temperature of the walls reached that of the room, a set of observations was made. After one more cycle of the hot and cold storage, the wallettes were returned to the drying room and the final observations taken after reaching temperature equilibrium. Shown in table 7 are the coefficients of thermal expansion of each of the walls, together with the maximum amounts of shrinkage corrected for temperature, as evidenced in the drying room and in the laboratory prior to drying them. These shrinkages are the changes in length, based on original readings taken at an age of 2 or 3 days.

TABLE 7.—*Shrinkage and thermal—expansion coefficients*

Aggregate	Grits		Pea gravel		¾-in. gravel	
Nominal cement content, bags per cu yd [a]	3	2½	3	2½	3	2½
Method of placing	Loose	Tamped	Loose	Tamped	Loose	Tamped
Coefficient of thermal expansion per °F [b]	6.1×10^{-6}	6.1×10^{-6}	6.1×10^{-6}	6.0×10^{-6}	6.1×10^{-6}	5.9×10^{-6}
Total shrinkage:						
Laboratory storage, % [c]	0.038	0.026	0.029	0.025	0.012	0.007
Drying-room storage, % [c]	.052	.037	.041	.033	.015	.009

[a] See table 2 for actual cement content.
[b] Determined in the range of 10° to 100° F.
[c] Corrected for temperature.

TABLE 8.— *Rise of water due to capillarity*

Aggregate	Grits		Pea gravel		¾-in. gravel	
Nominal cement mixture ..... bags per cu yd[a]	3	2½	3	2½	3	2½
Method of placing	Loose	Tamped	Loose	Tamped	Loose	Tamped
Rise in 1 hour:						
Specimen 1 ..... in	1.25	1.50	0.90	1.00	1.50	0.50
Specimen 2 ..... in	1.00	1.25	1.00	1.00	0.50	.75
Average	1.1	1.4	1.0	1.0	1.0	0.6
Rise in 24 hours:						
Specimen 1 ..... in	3.00	2.00	1.75	1.75	1.75	1.50
Specimen 2 ..... in	1.50	2.00	1.50	1.50	2.00	1.75
Average	2.2	2.0	1.6	1.6	1.9	1.6
Rise in 7 days:						
Specimen 1 ..... in	6.75	5.00	3.25	3.25	3.50	3.25
Specimen 2 ..... in	6.25	4.50	2.50	2.50	4.00	3.50
Average	6.5	4.7	2.9	2.9	3.8	3.4

[a] See table 2 for actual cement content.

5. Water Penetration Due to Capillarity

From the broken halves of the transverse-test walls, specimens 6 in. thick, 10 in. wide, and 15 in. high were stood vertically in pans containing ⅛ in. of water. This was done in a room where the relative humidity was 80 to 85 percent and the temperature 72° to 75° F.

The maximum rise of water in the specimens was observed at 1 hr, 24 hr, and at 7 days, and these values are given in table 8. Two specimens of each set were used, one from a monolithic wall, and the second from a transverse-joint wall.

6. Resistance to Rain Penetration

(a) *Specimens*

The six specimens used for the water-permeability tests were about 51 in. high, 41 in. wide, and 6 in. thick, with each of the three aggregates represented with the concrete tamped or placed loose. They were built on supporting channels with a 2-in. mortar base containing a copper flashing projecting at the back, which collected any water penetrating the face during test. Similar to the heat-transfer walls, the front face, edges, and top were finished with ⅛ in. of stucco. These walls were aged at least 1 month indoors before being tested. The walls made of grits are shown in figure 8. On the left is the face of the tamped wall to which the stucco was later applied, and on the right may be seen the back of the wall with the concrete placed loose and the flashing embedded in the 2-in. mortar base.

(b) *Test Equipment and Procedure*

The water-permeability test is described in BMS82, Water Permeability of Walls Built of Masonry Units. The walls were given a preliminary test of 2 days, and then put in a drying room until they had reached constant weight before the final test. The specimens were supported on metal skids, and when clamped in position, the exposed face formed one side of a pressure chamber. An air pressure of 10 lb/ft^2 above atmospheric was maintained in the chamber, and water from a perforated tube was sprayed near the top edge of the exposed face at the rate of 40 gal/hr.

The following observations were made during the test: Time required for the appearance of moisture (dampness) and of visible water on the backs of the walls; time for leakage of water from the flashing, and the maximum rate of leakage; extent of damp area on the back, including that produced by the capillary rise of moisture from water on the flashings.

(c) *Test Results*

The arbitrary method of rating the performance, as given in BMS82, was employed. All the walls were judged to be excellent, since they had no visible water above the flashings in 1 day, no leakage, and less than 25 percent of the wall area was damp in 5 days.

7. Bond Strength

Bond pull-out specimens were made to determine the value of the bond of porous con-

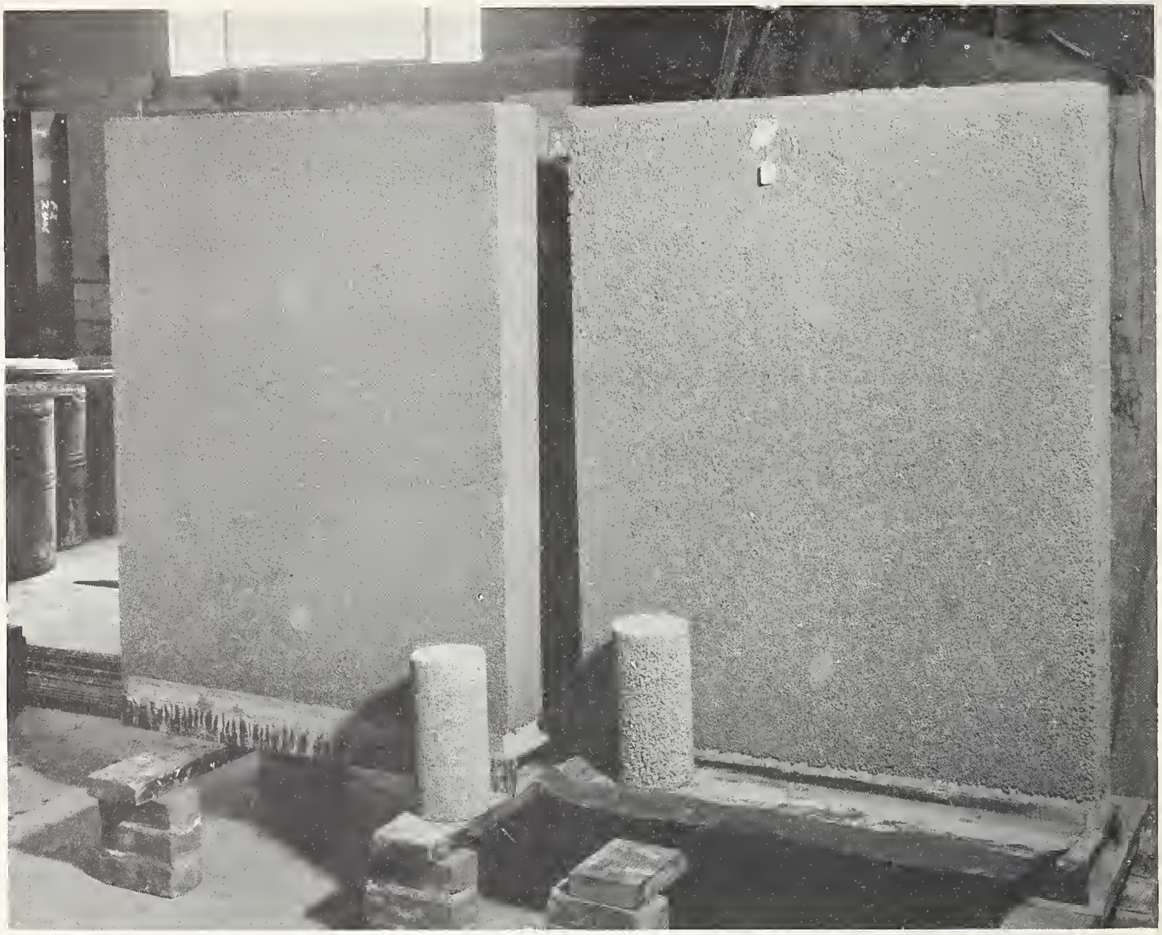

FIGURE 8.—*Water permeability specimens of porous concrete containing grits and before stuccoing.*

On the left is face of wall of tamped concrete; on the right is back of wall of loose concrete.

crete as compared with that of the usual structural concrete. Porous concrete tamped in place, and made with pea gravel, using 2½ bags of cement per cu yd, was compared with an ordinary concrete with a compressive strength of 2,500 lb/in.^{2} in the proportions of 1:2.8:3.2, by volume of cement, sand, and ¾-in. gravel. The steel used in both sets of specimens was the ¾-in. round deformed bar made by the Atlantic Steel Co.

Three specimens of each type of concrete were made, 6 by 6 by 12 in. long, the bar being centered in the molds as shown in figure 9. The specimens were made with the bar in the horizontal position; the porous concrete was tamped in place, and the regular concrete compacted with an electric vibrator. Three compressive-test cylinders of each type of concrete were made. All the specimens were stored in air in the laboratory and tested at the age of 28 days.

For testing, the bond specimens were set up as shown in figure 10. The plaster-capped base was in contact with a spherical bearing block having a 1-in. hole in the center, and a 0.0001-in. micrometer dial was used to measure the amount of slip of the bar at the free end.

Loads were applied to the bar, and the amount of slip as shown by the micrometer dial was recorded for various loads. The average bond stresses for each bar were computed for a first slip of 0.0001 in. and for the maximum load and are given in table 9.

For the porous concrete, the yield point of the steel had not been reached at bond failure, whereas in the ordinary concrete the yield point of the steel was exceeded. All specimens failed by splitting longitudinally through the center

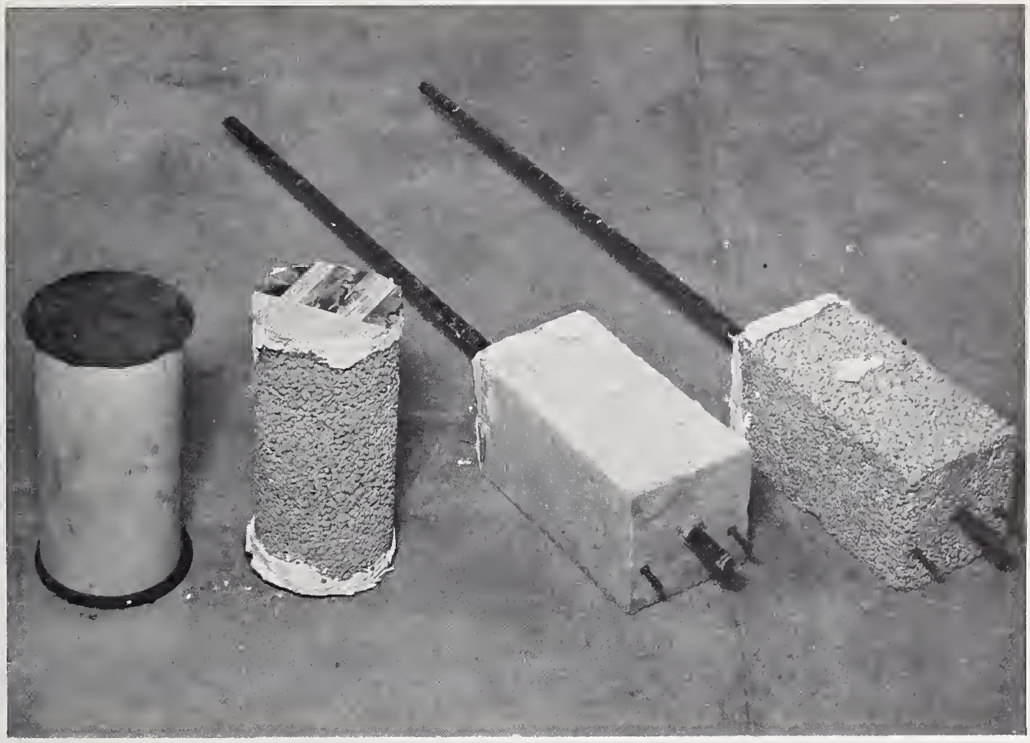

FIGURE 9.—*Bond pull-out test specimens.*

in the plane parallel to the finished surface in the position they were molded.

8. RESISTANCE TO FAILURE BY DIAGONAL TENSION

To determine resistance to diagonal tension, six beams were made of pea gravel, using 2½ bags of cement per cu yd, the concrete being tamped in place. The beams were 4 ft 10 in. long, 6 in. wide, 13½ in. deep, with reinforcing steel at a depth of 12 in. Two ⅝-in. round deformed bars, hooked at each end, were used as reinforcement, the bars in three of the beams being given a coating of cement grout immediately before placing them; in the other three beams the reinforcing was placed as delivered.

In the tests a 4-ft span was used with the beam loaded at midspan. The maximum load was recorded, as was the load for the appearance of the first crack. The observed data are given in table 10, and it is to be noted that specimen 3, using the uncoated steel, failed by yielding of the tensile reinforcement, whereas the other five failed principally by diagonal tension.

TABLE 9.—*Bond strengths as determined by pull-out specimens*

	Porous concrete, 2½-bag mix, tamped, pea gravel				Regular concrete 1:2.8:3.2 by volume			
Specimen	1	2	3	avg	1	2	3	avg
Bond stress:								
At slip of 0.0001 in. lb./in.²	146	221	177	181	221	279	226	242
At maximum load lb./in.²	313	376	306	332	934	(1)	930	930
Compressive strength:								
Cylinders lb./in.²	551	594	530	560	2,430	2,680	2,760	2,620

[1] Loading discontinued at yield point of steel.

TABLE 10.—*Resistance to diagonal tension in beams*

Specimen	Computed shearing stresses		Compressive strength of cylinders
	First crack	Maximum load	
BARS UNCOATED			
	lb/in.²	*lb/in.²*	*lb/in.²*
1	28	56	546
2	30	74	639
3	36	100	759
Average	31	77	648
BARS COATED WITH CEMENT GROUT			
1	39	85	709
2	40	83	821
3	35	71	824
Average	38	80	785

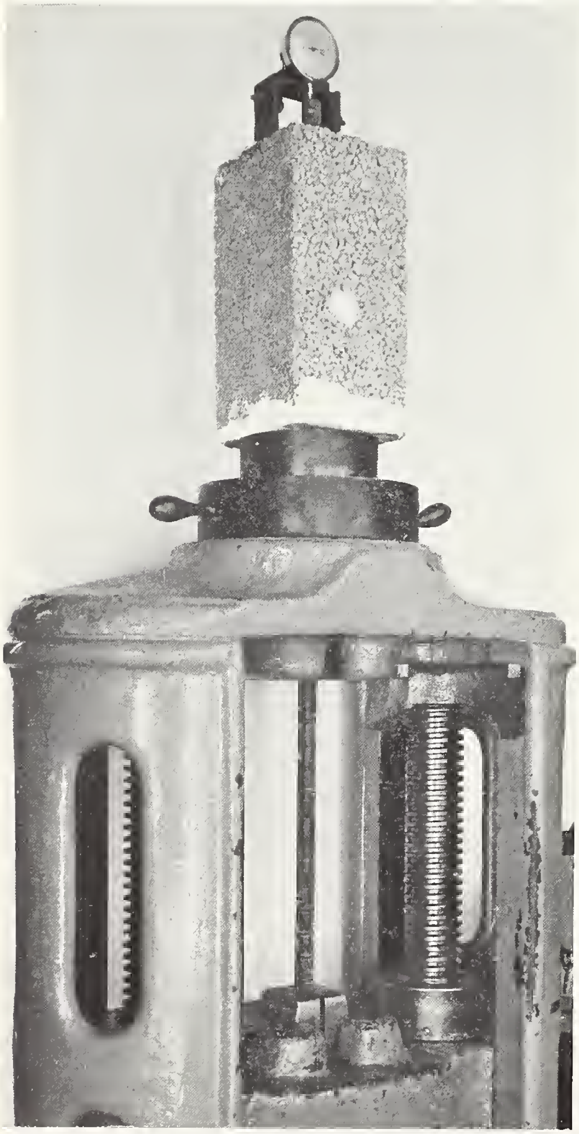

FIGURE 10.—*Porous-concrete specimen in bond pull-out test.*

V. SUMMARY

Specimens of porous concrete consisting of cement and each of three uniform-sized gravels as aggregates (grits, pea gravel, ¾-in. gravel) were made and tested after preliminary studies into the techniques of mixing and placing had been completed. The strengths obtained in these preliminary studies led to the use of two mixtures for the tests, namely: 3 bags of cement per cu yd in concrete placed loose and 2½ bags of cement in concrete tamped in place. A summary of the results of the various tests performed, follows: [1]

The weight per cubic foot tended to increase with increase in size of aggregate, with a range of 97 to 105 lb/ft³ for that placed loose and 110 to 115 lb/ft³ for that tamped in place. The water-cement ratio, by weight, however, decreased with increase in size of aggregate, ranging from 0.50 to 0.40 for the loose and 0.50 to 0.44 for the tamped concrete.

The modulus of rupture for the monolithic walls was about 100 lb/in.², tending to be slightly less than this value for the concrete placed loose and more for concrete placed by tamping. This value is about one-fourth of that expected for a dense concrete with a compressive strength of 2,500 lb/in². The transverse strengths of walls containing a horizontal construction joint were considerably less than for walls with no joints; with the tamped porous concrete, the strength of the joint averaged less than 25 percent of that of the monolithic wall.

The compressive strength of the tamped cylinders ranged from 600 to 900 lb/in.², and was a fair indication of the strength in walls

[1] The indications of this data on strength, shrinkage, resistance to rain penetration, and heat transfer are similar to those reported by the Building Research Board of Great Britain, namely:

"The optimum proportion of cement to aggregate was found to be surprisingly low, a ratio of 1 part of cement to 18 parts of aggregate graded from ⅜ in. to ¾ in. being found sufficient to cover the stones and develop a compressive strength at three months of over 400 lb/in.² with either gravel or dolerite.

"In respect of drying, shrinkage, and expansion on wetting, the open-textured concrete does not differ significantly from typical dense 1:2:4 concrete.

"Rendered panels of open-textured concrete 9 in. thick proved quite resistant to rain penetration. The thermal conductivity was closely similar to that of solid brickwork and dense concrete, a result which was not anticipated, the high proportion of pore space being expected to improve the thermal insulation."

From report of the Director of Building Research for the year 1939, page 45 (His Majesty's Stationery Office, London).

8 ft high and of the same mixture. When the concrete was placed loose, the walls yielded strengths of 500 to 650 lb/in.^{2}, these values being 50 to 150 lb/in.^{2} higher than the strengths of their respective cylinders. The values for secant modulus of elasticity at a stress of 200 lb/in.^{2} ranged between one and two million lb/in.^{2}, tending to increase with increased size of aggregate.

Resistance to heat transmission decreased as the size of aggregate increased, the values of thermal transmittance, U, varying from 0.64 to 0.87 Btu/hr ft^2 °F for 6-in. walls, these being the corrected values for a 15-mph wind outside and zero wind inside, the standard test condition recommended by the ASHVE "Guide." The "Guide" lists U values of 0.77 to 0.88 for dense concretes of various ages and mixtures.

Resistance to rain penetration of walls to which ⅝-in. stucco was applied was excellent.

The coefficient of thermal expansion averaged 0.000006/° F, approximating that of the gravel used as aggregate.

The amount of shrinkage ranged from 0.009 to 0.052 percent for the dry walls and seemed to decrease with increase in size of gravel and with the amount of compacting.

The rise of water by capillarity in walls of porous concrete ranged from 3 to 6½ in. at 7 days, the greater value occurring in the concrete with grits placed loose.

The bond stress at first slip between reinforcing steel and tamped porous concrete made of pea gravel and 2½ bags of cement per cu yd was about three-fourths of that obtained for a regular concrete with a compressive strength of 2,500 lb/in.^{2} However, the maximum bond strength developed by the pull-out specimens of porous concrete was only about one-third that of the ordinary concrete.

The computed shearing stress in the beams at failure was about 80 lb/in.^{2}, this value being about one-half of that expected for a regular concrete with a compressive strength of 2,500 lb/in.^{2} The resistance to failure by diagonal tension did not change appreciably when the reinforcing bars were coated with a cement-water grout immediately before placing.

The assistance of the Federal Public Housing Authority, represented by A. M. Korsmo and B. M. Thorud, in planning the investigation, supplying information on methods of mixing and placing concrete, and in analyzing the results of the preliminary studies is gratefully acknowledged. Mr. Korsmo also reviewed the manuscript of the report and made valuable suggestions for its improvement.

The heat-transfer properties were determined by H. E. Robinson, of the Bureau's Heat Transfer Section; the water-permeability properties by C. C. Fishburn, of the Masonry Construction Section.

WASHINGTON, December 19, 1942.

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