Properties of Some Lightweight-Aggregate Concretes With and Without an Air-Entraining Admixture

Building Materials and Structures Report BMS112

United States Department of Commerce
National Bureau of Standards

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Properties of Some Lightweight-Aggregate Concretes With and Without an Air-Entraining Admixture

by Perry H. Petersen

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Foreword

This report describes an investigation of the physical properties of several lightweight-aggregate portland cement concretes made with burned shale or expanded slag, undertaken in cooperation with the Federal Public Housing Authority to determine the application of such a concrete in the construction of housing.

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

E. U. CONDON, *Director*.

Properties of Some Lightweight-Aggregate Concretes With and Without an Air-Entraining Admixture

by Perry H. Petersen

ABSTRACT

The physical properties of several lightweight aggregate portland cement concretes made with burned shale or expanded slag were investigated at the National Bureau of Standards. Three grades of concrete using each aggregate were made. Air-entrainment of greater than 20 percent is reported for the mixtures leanest in cement, an air-entraining admixture being used to increase the workability of all but the richest concretes. Compressive, transverse, and bond strengths are given as well as resistance to heat transfer, rain penetration, and water penetration by capillarity. Also included are the coefficients of thermal expansion, shrinkage, and values for change in length due to wetting and drying.

CONTENTS

I. Introduction

The purpose of an investigation conducted at the National Bureau of Standards was to determine the physical properties of several lightweight-aggregate concretes in anticipation of their use in the monolithic construction of buildings. These lightweight aggregates of burned shale or expanded slag incorporate features that tend to improve heat insulation more than the aggregates used for dense concrete. However, if the cement content is low (3 sacks/yd^3), workability is so poor that placement of the concrete is extremely difficult. Instead of flowing into the forms, the mixture is harsh and the mixing water tends to settle, taking some cement with it. This fault may be overcome by entraining air in the concrete through the use of an admixture, the entrained air totaling 20 to 25 percent by volume. When the cement content is increased to 10 or 11 sacks/yd^3 of concrete, there is no need for entraining air to increase workability.

For tests described in this report, burned shale and expanded slag were each used as aggregates in three grades of concrete ranging upward from a

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strength of 500 lb/in ^{2}. An air-entraining agent was added to the two leanest mixtures for each aggregate but was omitted in the concretes which were richest in cement.

The properties covered in this investigation include compressive, transverse, and bond strengths, resistance to heat transfer, water penetration by capillarity and rain penetration. Values were determined also for shrinkage, for the coefficients of thermal expansion, and for changes in length due to wetting and drying.

II. Materials

The cement was a portland cement conforming to the requirements of Federal Specification SS-C-191b Amendment 1.

The burned shale was a lightweight cellular aggregate made by burning a certain clay and shale to incipient fusion. The material was obtained in two sizes, coarse and fine. The sieve analyses, absorptions (surface dry), bulk specific gravities, and the weights per cubic foot of dry material are given in table 1.

The expanded slag was a lightweight cellular aggregate made from molten hot slag as it comes from the blast furnace by agitating and cooling it rapidly in an atmosphere of steam. This material also was furnished in two sizes, coarse and fine. The physical properties are given in table 1.

The air-entraining admixture was a commercial product made expressly for entraining air in concrete.

Table 1. *Data on aggregates*

Aggregate	Burned shale		Expanded slag	
Grade	Coarse	Fine	Coarse	Fine
Sieve analysis; aggregate passing United States Standard Sieve:				
½ in ... percent	100	-------	100	-------
⅜ in ... do	88	-------	98	-------
No. 4 ... do	20	100	34	100
8 ... do	5	97	13	96
16 ... do	4	64	11	76
30 ... do	3	38	10	49
50 ... do	3	25	10	30
100 ... do	3	17	9	21
200 ... do	2	12	7	14
Absorption (surface dry)[a] 48 hr at 70° F ... percent	15.8	10.9	36.8	19.0
Bulk specific gravity (oven dry)[a]	1.09	1.54	1.09	1.46
Weight, loose, dry ... lb/ft ^{3}	37	45	40	57

[a] Absorption and bulk specific gravity determined by ASTM methods of test C 127–42 and C 128–42, respectively.

III. Concrete

The cement and lightweight aggregates of burned shale and expanded slag were proportioned by trial batches to produce concretes ranging from a low to a high cement content. Three mixtures of each were selected to produce a low-, medium-, and a high-strength concrete.

The burned-shale aggregate, in the original sacks, was completely immersed in water for 48 hr and then was allowed to drain, while still sacked, for 24 hr. The moisture content was determined, the amount of free water being included as mixing water in the proportioning of the materials. The expanded-slag aggregate was used in the dry condition as recommended by producers of this material.

The materials were proportioned by weight and the concrete was mixed in a standard 6-ft^3 rotary drum-type mixer. The air-entraining agent, when used, was introduced with the water and the time of mixing was in all cases about 5 minutes, as trial mixes indicated that this was the minimum interval needed to secure complete air entrainment.

All specimens were hand puddled. The forms were stripped at one day, and then the specimens were cured with wet burlap to an age of either 7 days or 28 days as required. They were then stored in the laboratory until tested.

Table 2 lists the data obtained on the fresh concrete, the weight and absorption of the dry concrete, and the compressive strengths of 6- by 12-in. cylinders after aging 28 days. The weight of dry concrete was obtained after drying the specimens to constant weight in a chamber maintained at 122° F (50° C) and a lowered humidity (approximately 20 to 30 percent) obtained with pans of calcium chloride. The cement-voids ratio shown in the table is based on the absolute volume of all the ingredients, the voids including entrained air as well as all water other than that absorbed in the aggregate. Water absorption was determined on oven-dried specimens (220° F) by immersing them in water at 70° F for 24 hr.

Water penetration due to capillarity was determined by placing three specimens of each concrete in a pan containing water ⅛ to ¼ in. in depth. The specimens were 4 by 4 in. in cross section and about 12 in. high. Observations were made at 1 hr and at 7 days to determine the height the water rose due to capillarity. The observed heights are given in table 2.

TABLE 2. *Proportions of ingredients; density and absorption of concretes*

	Aggregate					
	Burned shale			Expanded slag		
Cement content, sacks/$yd.^3$	3.0	5.4	9.9	4.4	6.9	11.0
Air-entraining agent, by weight of cement, percent	.50	.25	None	.50	.25	None
Proportions, by loose volume, dry:						
Portland cement	1.0	1.0	1.0	1.0	1.0	1.0
Fine aggregate	6.2	3.2	1.4	2.7	1.5	0.8
Coarse aggregate	3.0	2.0	1.5	2.2	1.6	1.2
Slump, in.	2.5	4.3	6.4	4.0	6.0	5.6
Cement voids [a] ratio by absolute volume	.122	.247	.611	.174	.303	.652
Entrained air, by volume [b], percent	20.8	13.9	([c])	(24)	(18)	([c])
Weight of concrete:						
Fresh, lb/$ft.^3$	74.0	83.4	101.2	72.9	81.3	102.8
Dry, lb/$ft.^3$	60.3	71.4	88.2	65.1	72.8	96.2
Water absorption, 24 hr at 70° F by dry weight, percent	23.1	14.0	10.0	21.4	14.6	10.0
Capillary rise of water:						
At 1 hr, in.	1.9	1.3	1.0	.9	1.1	.9
At 7 days, in.	8.5	4.7	4.0	6.3	4.6	4.8
Compressive strength [d] at 28 days:						
Cured 7 days wet, 21 days in air, lb/$in.^2$	530	2,240	6,090	770	1,660	3,540

[a] Voids=entrained air and mixing water.
[b] Values in parentheses are estimated.
[c] Negligible.
[d] See table 3 for additional data.

IV. Description of specimens and test results

1. Compressive strength

The specimens for compressive strength tests included 6- by 12-in. cylinders and some wallettes 8 by 30 by 30 in. The wallettes were used primarily to obtain values of shrinkage and were then tested in compression at the termination of those observations.

Values for the secant modulus of elasticity were obtained on cylinders wet-cured for 28 days by means of Tuckerman extensometers with a 6-in. gage length. The moduli were determined at stresses of 200, 800, and 2,000 lb/$in.^2$, respectively, for the three grades of concrete. These values and the compressive strength values are given in table 3.

TABLE 3. *Compressive and flexural strengths of concrete specimens* [a]

	Aggregate					
	Burned shale			Expanded slag		
Cement content, sacks/$yd.^3$	3.0	5.4	9.9	4.4	6.9	11.0
Compressive strength:						
Cylinders, 6- by 12-in.						
Age 7 days, wet-cured, lb/$in.^2$	230	1,110	4,250	310	960	2,560
Age 28 days, wet-cured, lb/$in.^2$	480	1,730	5,720	590	1,510	3,380
Age 28 days, 7 wet- and 21 air-cured, lb/$in.^2$	530	2,240	6,090	770	1,660	3,540
Age 2 yr, 7 days wet-cured, lb/$in.^2$	650	2,590	5,850	860	1,570	3,100
Wallettes, 30- by 30- by 8-in.						
Age 2 yr, 7 days wet-cured, lb/$in.^2$	1,030	2,970	5,380	810	1,590	3,150
Secant modulus of elasticity, 6- by 12-in. cylinder:						
Age 28 days wet-cured:						
At 200 lb/$in.^2$, lb/$in.^2$	720,000	----------	----------	615,000	----------	----------
At 800 lb/$in.^2$, lb/$in.^2$	----------	1,240,000	----------	----------	1,050,000	----------
At 2000 lb/$in.^2$, lb/$in.^2$	----------	----------	2,170,000	----------	----------	2,000,000
Modulus of rupture in flexure of 4- by 4-in. bars:						
Age 28 days, 7 wet- and 21 air-cured, lb/$in.^2$	153	398	690	183	333	656

[a] All values are the average for 3 specimens, except in the case of wallettes, of which there was only one specimen each.

2. Flexural Strength

Flexural strength tests were made on bars 4 by 4 in. in cross section and 30 in. long, at an age of 28 days. The bars were supported as a simple beam on a span of 24 in., and were loaded at the center with the screeded side of the concrete in compression. The computed values for the modulus of rupture are included in table 3.

3. Bond Strength to Reinforcement

Reinforced concrete beams were made of the two strongest grades of each concrete with two makes of bar represented. Bond strengths after 28 days of wet curing were determined for lengths of embedment of 10, 20, and 30 in. by making and testing beams of different lengths. A sketch of the beams is shown in figure 1.

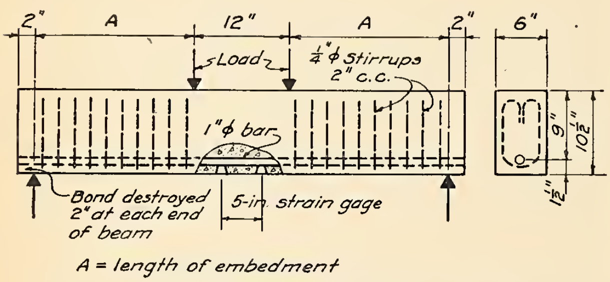

Figure 1. *Sketch of beams for bond strength tests.*

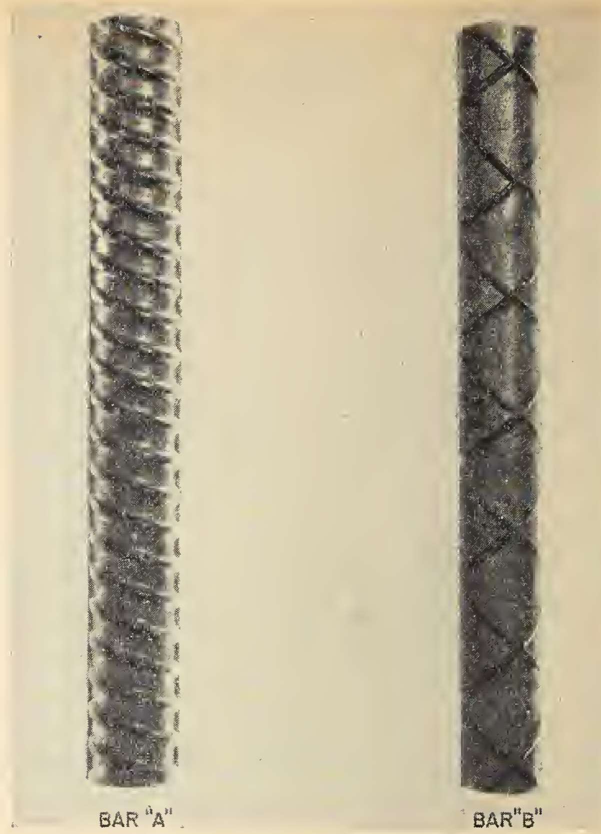

Figure 2. *Types of bars for bond strength tests.*

The two bars represented are shown in figure 2 and have nominal diameters of 1 in. The deformations on bar *A* are of the double helix pattern, reversing direction on the two faces of the bar. The deformations on bar *B* are of the diamond-patterned type. The tensile properties determined for each bar are given in table 4.

Table 4. *Tensile properties of reinforcing bars*

	Bar *A*	Bar *B*
Cross-sectional area……in.²	0.796	0.788
Yield point……lb/in.²	60,400	52,000
Tensile strength……lb/in.²	94,200	92,300
Elongation in 8 in……percent	18.8	23.1

Most of the specimens exhibited bond failures, but in some the reinforcing bars yielded in tension. Where the latter occurred, bond stress values were based on the load at which yielding of the reinforcement occurred. Whittemore strain-gage readings on a 5-in. gage length were made on the steel at the center of the beam through holes in the concrete. Slip at the ends of the bar was measured by using 0.0001-in. dial indicators fastened to two lugs embedded in the concrete, the dial stem being in contact with the end of the bar.

The computed bond stresses at an initial slip of 0.001 in., and the bond strength are given in table 5.

Table 5. *Bond strengths between concrete and reinforcement bars*

	Aggregate			
	Burned shale		Expanded slag	
Cement content……sacks/yd.³	5.4	9.9	6.9	11.0
Compressive strength, 28 da wet……lb/in.²	1,730	5,720	1,510	3,380
Bond stress at 0.001 in. slip:				
Bar A:				
10-in. embedment……lb/in.²	320	647	283	440
20-in. embedment……lb/in.²	425	600	320	500
30-in. embedment……lb/in.²	420	[a] 520	307	[a] 520
Bar B:				
10-in. embedment……lb/in.²	182	528	212	430
20-in. embedment……lb/in.²	175	425	165	340
30-in. embedment……lb/in.²	157	[a] 450	180	[a] 450
Bond strength:				
Bar A:				
10-in. embedment……lb/in.²	341	820	318	440
20-in. embedment……lb/in.²	506	[a] 790	374	610
30-in. embedment……lb/in.²	[a] 520	[a] 520	328	[a] 520
Bar B:				
10-in. embedment……lb/in.²	310	619	231	530
20-in. embedment……lb/in.²	385	[a] 680	221	544
30-in. embedment……lb/in.²	267	[a] 450	252	[a] 450

[a] Bond stress at tensile yielding of bars.

4. Heat-transfer properties

Two types of specimens of each concrete were made for the heat-transfer tests, one for use in the shielded hot box and one to be tested by means of the guarded hot plate.

(a) Shielded hot-box tests

The walls for the shielded hot-box tests were 100 in. high, 8 in. thick, and 56 in. wide, and were tested at an age of 18 to 24 months, having been in storage in the laboratory for that length of time. They had been wet-cured for the first 7 days and exposed to the air for the remainder of the period.

The heat-transfer section of this bureau conducted the tests in a shielded hot-box apparatus designed for the purpose. 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 a watt-hour meter was closely equivalent to the heat energy transferred through the portion of the wall covered by the metering box. The temperatures in the metering and shielded boxes were the same and were kept at 70° F; the temperature in the cold box was kept at 0° F, making the mean temperature approximately 35° F. Air temperatures and surface temperatures on both sides of the wall were measured by means of thermocouples.

(b) Guarded hot-plate tests

The specimens for the guarded hot-plate tests were 8 by 8 in. in plan and about 1 in. in thickness. They were cut from an 8-in. wall sample with one 8-in. dimension parallel to the thickness of the wall the other parallel to the height of the wall, and the 1-in. dimension parallel to the width of the wall.

The apparatus consisted of an electrically heated flat hot plate, 8 in. square, flanked on each side by a cold plate that was cooled by a flow of water at constant temperature. Two like specimens of each concrete were used, one being placed on each side of the hot plate and between it and the adjacent cold plate. The heat flowing through a central metering area 4 in. square was measured and the heat conductivity of the material computed. The average mean temperature of the hot-plate specimens was approximately 68° F. Immediately after testing, these specimens were dried for 24 hr at 230° F in order to ascertain the moisture content of the concrete at the time of test.

(c) Results of heat-transfer tests

The results of the observations on heat-transfer tests are given in table 6. The heat transmission is expressed in two ways: by the over-all heat transmittance, U, of the 8-in. wall, and by the thermal conductivity, k. Both heat-transfer coefficients were computed for each type of test to provide a comparison of values obtained by the two methods. It is believed that the moisture content of the large walls was considerably greater than that of the small specimens used in the hot-plate tests, and that the higher values obtained in the hot-box tests are due to this greater moisture content. The magnitude of this effect is indicated in table 6 by the two hot-plate tests made at different moisture contents on the burned-shale specimen leanest in cement.

TABLE 6. *Heat-transfer coefficients*

	Aggregate						
	Burned shale				Expanded slag		
Cement content .... sacks/yd.³	3.0		5.4	9.9	4.4	6.9	11.0
Shielded hot-box data:							
Thickness of walls .... in.	8.05		8.06	8.02	8.00	8.00	8.00
Corrected thermal transmittance,ᵃ U	0.26		0.32	0.41	0.24	0.30	0.38
Thermal conductivity,ᵇ k	2.60		3.44	4.88	2.41	3.13	4.34
Guarded hot-plate data:							
Thickness of specimen .... in.	1.02		0.99	1.06	1.06	1.03	1.06
Dry density .... lb/ft.³	61.0		68.8	84.0	61.5	71.4	94.4
Moisture content as tested .... percent	1.7	7.3	3.1	5.0	2.5	3.5	4.5
Thermal conductivity,ᵇ k	1.87	2.31	2.29	3.01	1.77	2.27	3.42
Computed value of thermal transmittance for 8-in. wall,ᵃ U	0.20	0.24	0.24	0.29	0.19	0.23	0.32

[a] U=number of Btu per hour transmitted through each square foot of specimen for each degree Fahrenheit difference in temperature between the air on the two sides for a condition of still air on the warm side and a 15-mph wind on the cold side.

[b] k=number of Btu per hour transmitted through each square foot of specimen for each degree Fahrenheit temperature difference in the material per inch f thickness.

5. Thermal-expansion coefficients

Six specimens, 1½ in. square and 9 in. long, were cut from specimens of each concrete. Data were obtained with a 6-in. Tuckerman optical strain gage operating on specimens placed in a temperature-controlled box equipped with observation portholes. Readings were made at two extremes of temperature, 104° F (40° C) and 14° F (−10° C), a full cycle requiring 24 hr. Measurements were

Table 7. *Length changes due to temperature, wetting and drying, and drying shrinkage*

	Aggregate					
	Burned shale			Expanded slag		
Cement content ... sacks/yd ^{3}	3.0	5.4	9.9	4.4	6.9	11.0
Coefficient of thermal expansion ... 10^{-6}/° F	3.6	4.1	4.5	5.1	5.5	6.2
Shrinkage of 8-in. thick wallettes in laboratory air:						
At 1 yr ... 10^{-6} in./in.	−440	−180	[a]+160	−800	−710	−360
At 2 yr ... 10^{-6} in./in.	−660	−410	[a]+160	−960	−1,060	−710
Changes in length [b] during wetting and drying at 70° F ... 10^{-6} in./in.	−270	−500	−600	−400	−630	−970

[a] The plus sign denotes an expansion of 0.000160 in./in.
[b] Values signify shrinkage on drying cycle and are equal and opposite to expansion on wetting.

made for a number of cycles until the readings indicated no progressive changes in length. The temperature of the air surrounding the specimens was determined with calibrated copper-wire resistance thermometers and was controlled with a bimetal thermoregulator to ±0.2 deg F.

The coefficients of thermal expansion were determined for six like specimens, and the average for each concrete is reported in table 7.

6. Shrinkage

Shrinkage was measured on wallettes 8 in. thick, 30 in. high, and 30 in. wide. Changes in the vertical direction beginning at an age of 1 week were obtained with a 20-in. Whittemore strain gage. The specimens were stored in laboratory air, and measurements were made over a period of 2 years.

Values for change in length due to wetting and drying were also obtained. These measurements were made using a vertical comparator on specimens 1½ in. square and 7 in. long; the specimens were cut from larger pieces of the concrete. When 18 to 24 months old, they were fully wetted for a week in water at 70° F, then dried to constant length at 70° F and 40-percent relative humidity. They were then immersed for 48 hr. and again dried to constant length, several of these cycles being made. Measurements of changes in length were noted from the start, and it was found that there was but a slight change from cycle to cycle.

Values of shrinkage in laboratory air and those of change in length during wetting and drying are shown in table 7.

7. Rain Penetration

The six specimens used for the water permeability tests, one of each mix, were about 51 in. high, 41 in. wide, and 8 in. thick. They were built on supporting channels with a 2-in. mortar base containing a copper flashing projecting at the back. The surfaces were not finished in any way; the walls were tested at an age of 3 months in their original condition.

The water-permeability test is described in Building Materials and Structures Report BMS82, Water permeability of walls built of masonry units.[1] 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 pressure 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 arbitrary method of rating the performance as given in BMS82 was employed. All the walls were judged to be excellent because no visible water appeared above the flashings in 1 day, and in 5 days there was no leakage and less than 25 percent of damp wall area.

[1] Obtainable from the Superintendent of Documents, Government Printing Office, Washington 25, D. C., for 20 cents.

V. Summary

Specimens of lightweight-aggregate concretes made with burned shale or an expanded slag as the sole aggregates were tested for various physical properties.

Three grades of each concrete were made: a lean, an intermediate, and a rich concrete. The cement contents were 3.0, 5.4, and 9.9 sacks/yd^3, respectively, for the concretes with burned shale as the aggregate and 4.4, 6.9, 11.0 for the concretes made with expanded slag. An air-entraining agent was used with the portland cement in all but the richest mixtures of each type of concrete. The leanest mixtures with each aggregate had compressive strengths of 500 to 800 lb/in.^{2} and dry weights of 60 to 65 lb/ft^3. Walls of this low-cement, high-void concrete possess heat-transfer properties suitable for insulation in some types of buildings. Hot-plate test values of 1.8 and 1.9 Btu in. hr^{-1} ft^{-2} $°F^{-1}$ for thermal conductivity compare very favorably with values of 10 to 16 for ordinary dense concrete.

Heat transfer, compressive strength, and density all increased with increase in cement content, but thermal conductivity increased only to 3.0 and 3.4 for the dense mixtures, which is still a relatively low value for monolithic concrete.

Tests show that concrete with a compressive strength of 6,000 lb/in.^{2} can be made by using burned-shale aggregate; the expanded-slag mixture with a cement content of 11 sacks/yd^3 had a compressive strength of 3,500 lb/in^2. The ratio of compressive to transverse strengths was about the same as for ordinary sand and gravel concrete, although more cement was required with the lightweight aggregates to obtain equivalent strengths. The modulus of elasticity was 2,170,000 lb/in.^{2} for a burnt shale aggregare concrete of 5,000-lb/in.^{2} compressive strength.

Bond strength between the concrete and the steel reinforcement was about the same as for ordinary dense aggregate concrete of the same compressive strength.

Coefficients of thermal expansion for the lightweight-aggregate concretes made with burned shale ranged from 3.6 to 4.5×10^{-6} per ° F, and from 5.1 to 6.2×10^{-6} for those made with expanded slag. All of the mixtures showed normal shrinkage ranging from 0.02 to 0.10 percent, except the burned-shale concrete richest in cement. This exhibited an expansion of almost 0.02 percent when stored in laboratory air for a period of one year. Length changes during wetting and drying ranged from 270 to 600×10^{-6} for the burned shale aggregate concretes and from 400 to 970×10^{-6} for the expanded slag aggregate concretes; they were smallest for the lean concretes and largest for the rich concretes.

Resistance of walls to rain penetration was shown to be excellent.

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, November 28, 1947.

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