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For The Atomic Energy Commission

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Chief, Declassification Branch

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Metallurgy and Ceramics

BATTELLE MEMORIAL INSTITUTE

ENGINEERING PROPERTIES OF HIGH-DENSITY CONCRETES

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SUMMARY

Methods were developed for measuring various engineering properties of high-density concretes. Data are presented on selected thermal properties of a limonite-iron concrete and the mechanical properties of the limonite-iron concrete, a magnesium oxychloride concrete, and a Portland cement concrete containing steel punchings and shot (no limonite). The properties which were determined included: thermal expansion, thermal conductivity, resistance to thermal stress, heat liberation during setting, effect of temperature and humidity on equilibrium water content, gas permeability, dimensional stability, compressive strength, modulus of elasticity, flexural strength, bonding strength, and shear strength.

INTRODUCTION

The experimental program on concretes for shielding reactors conducted at Battelle Memorial Institute for the past year has been concerned with the determination of the engineering properties of high-density concretes. Previous topical reports from this laboratory(1)* have covered, for the most part, the development of highly hydrated concretes with high density and satisfactory mechanical properties. The present report gives engineering data on high-density concrete.

The program was directed primarily toward a determination of selected thermal properties of a specific high-density concrete. This

* See Bibliography at the end of this report.

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limonite-iron concrete has been successfully used in shielding at the Brookhaven National Laboratory⁽²⁾. Minor attention was given to determining the mechanical properties of this concrete and of other high-density concretes.

The following properties of various high-density concretes were determined:

A. Thermal and general properties

1. Thermal expansion
2. Thermal conductivity
3. Resistance to thermal stress
4. Heat liberation
5. Effect of temperature and relative humidity on equilibrium water content
6. Gas permeability

B. Mechanical properties

1. Dimensional stability
2. Compressive strength
3. Compressional modulus of elasticity
4. Flexural strength
5. Bonding strength
6. Shear strength

In addition, a supporting investigation was made on the effects of different limonites on several of the above properties.

The thermal properties of high-density concretes are summarized in Table 1, and the mechanical properties are summarized in Table 2.

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TABLE 1. THERMAL PROPERTIES OF LIMONITE-IRON
HIGH-DENSITY CONCRETE

Thermal Property	Type of Limonite in Concrete	
	James Mine Ore*	Alabama Ore*
Coefficient of thermal expansion (inches/inch/°F.)	—	7.0×10^{-6}
Thermal conductivity at 100°F. [B.T.U./hr./sq. ft./°F./in.])	—	15
Resistance to thermal stress (temperature differential at which cracks were first observed)	No cracks at 180°F.	360°F.
Heat liberation (adiabatic temper- ature rise during setting)	43°F.	42°F.
Equilibrium moisture content (lbs. of H ₂ O/lb. of dry solids		
at 10% R.H. and 75°F.	0.058	—
at 100% R.H. and 75°F.	0.073	—
at 10% R.H. and 150°F.	0.040	—
at 100% R.H. and 150°F.	0.044	—
Gas permeability—coefficient of permeability, (lb./sec./sec., for 3-inch-thick specimen)	113×10^{-13}	34×10^{-13}

* Sources are given in the Appendix.

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TABLE 2. MECHANICAL PROPERTIES OF HIGH-DENSITY CONCRETES

DESCRIPTION	Storage Conditions, per cent R.H.	Linear Change, per cent expansion		Compressive Strength, psi		Modulus of Elasticity, psi x 10 ⁻⁶		Flexural Strength, psi		Bonding Strength, psi		Shear Strength, psi		Bulk Specific Gravity
		7 days	28 days	7 days	28 days	7 days	28 days	7 days	28 days	7 days	28 days	7 days	28 days	
M.O. Concrete (Plus Calgon) ⁽¹⁾	50	---	---	3170	1750	5.4	---	---	---	low	very low	---	---	5.2
M.O. Concrete (No Calgon) with Phosphated Punchings	50	---	---	3040	---	8.7	---	---	---	---	---	---	---	5.4
M.O. Concrete (Plus Calgon) with Phosphated Punchings	50	---	---	3850	2810	6.2	3.4	---	---	---	---	---	---	5.3
Portland High-Density Concrete with Punching and Steel Shot	Damp Sand	0	0.02 ⁽²⁾	2900	---	4.4	---	616	---	---	---	---	---	5.5
Limonite-Iron High-Density Concrete with Alabama Ore ⁽³⁾	Damp Sand	0	0.04 ⁽²⁾	4730	4330	7.4	7.4	867	966	high	high	---	833 ⁽²⁾	4.3
Limonite-Iron High-Density Concrete with Alabama Ore ⁽³⁾	50	---	---	3550	4070	5.6	3.4	---	---	fair	fair	---	---	4.2
Limonite-Iron High-Density Concrete with James Mine Ore ⁽³⁾	50	---	---	4660	---	5.1	---	---	---	---	---	---	---	---
Ordinary Portland Cement Concrete	Damp Sand	---	---	---	---	---	---	400	600	fair	---	590	---	2.4

(1) M.O. is magnesium oxyteloride - Calgon is sodium hexametophosphate

(2) These values were obtained after 2 months storage

(3) Sources are given in Appendix

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EXPERIMENTAL WORK

The work described in this report is divided into two sections; the first section reports the thermal and general properties of limonite-iron high-density concrete, and the second section gives the mechanical properties of high-density concretes. The high-density concretes investigated were M.O. (magnesium oxychloride) concrete, limonite-iron concrete, and Portland cement concrete containing punchings and steel shot (no limonite). Details concerning the composition, the materials used, and the preparation of specimens are given in the Appendix. The majority of the specimens were fabricated and stored in a room maintained at a temperature of 80°F. and a relative humidity of approximately 50 per cent. The specimens used in the heat-liberation test and in the test on the relation between equilibrium water content of limonite-iron concrete and relative humidity at various temperatures were prepared in a room maintained at 75°F. and a relative humidity of approximately 30 per cent.

Thermal and General Properties

Data on the thermal and general properties were obtained only for limonite-iron high-density concrete. Measurements were made on specimens containing James Mine ore and specimens containing Alabama limonite ore. Tests were conducted in a room maintained at 75°F. and a relative humidity of approximately 30 per cent, except for the tests on thermal expansion and gas permeability.

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Thermal Expansion

The coefficient of thermal expansion of limonite-iron high-density concrete was determined in the range from room temperature to 600°F. A Rockwell-Bristol dilatometer with a calibrated quartz system and a temperature-dilation recorder was used. A photograph of the apparatus is shown in Figure 1. The concrete specimens were 2-1/4 inches in diameter by 3 inches in height. A hole 1/4 inch in diameter extending 2-1/4 inches from the bottom was located axially for placement of a thermocouple.

The aggregate used in these tests contained iron punchings and Alabama limonite. The specimens were stored in damp sand for one week after casting and then at 50 per cent relative humidity prior to testing. Tests were made after storage periods of 8 days, 28 days, and 4 months. Representative curves of expansion versus temperature for each storage period are shown in Figure 2. The curves break at 212°F.; this break was greatest in those specimens which were stored for eight days and diminished in specimens stored for the longer periods. The break probably was due to loss of water during heating; a considerable amount of water came off the specimens that displayed the break. Because of the water loss, the curves probably are not reversible; a redetermination on the same specimens probably would show a displacement of the curves and a decrease or elimination of the break at 212°F. Table 3 shows the variation of the coefficient of thermal expansion with storage time.

The mean coefficient of thermal expansion was greater from room temperature to 212°F. than from 212°F. to 500°F. The mean coefficient

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FIGURE 1. THERMAL-EXPANSION APPARATUS

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FIGURE 2. THERMAL-EXPANSION CURVES OF LIMONITE-IRON, HIGH-DENSITY CONCRETE AFTER VARIOUS PERIODS OF STORAGE

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TABLE 3. MEAN COEFFICIENTS OF THERMAL EXPANSION OF
LIMONITE-IRON HIGH-DENSITY CONCRETE
AFTER VARIOUS PERIODS OF STORAGE

Description	Mean Coefficient of Thermal Expansion,* Inches/Inch/°F.	
	Range, 75-212°F.	Range, 212-500°F.
Concrete** stored for 1 week at 80°F. in damp sand	8.0×10^{-6}	6.4×10^{-6}
Concrete** stored for 1 month at 80°F. and 50% R.H.	8.7×10^{-6}	6.9×10^{-6}
Concrete** stored for 4 months at 80°F. and 50% R.H.	10.5×10^{-6}	7.0×10^{-6}

* Each value is the average for three test specimens.

** The aggregate in these specimens was composed of steel
punchings and Alabama limonite.

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also increased slightly with storage time both above and below 212°F. The average mean coefficient of specimens 8 days to 4 months old between 70 and 500°F. was 7.4×10^{-6} inches per inch per degree Fahrenheit.

Resistance to Thermal Stress

Stresses due to thermal gradients may be encountered in the concrete shield of a reactor. Proper design of a concrete shield requires knowledge of the thermal stress that the concrete will withstand. A test was designed to provide this information for limonite-iron concrete. The method of imposing a thermal stress on the concrete consisted of placing a thick-walled, tubular, concrete specimen in a bath of cracked ice and water and heating the interior with an electrical heating coil. Some specimens were subjected to a cyclic thermal-stress (thermal-shock) test. These specimens were heated in air by means of the internal heating coil and then were placed in the ice-water bath. After coming to equilibrium, the cycle was repeated, until cracks developed. A photograph of the apparatus is shown in Figure 3, and a schematic diagram is shown in Figure 4.

The test specimens were prepared by casting fresh concrete around a 7/16-inch O.D. porcelain tube located in the center of each mold. Two Number 24-gauge Chromel-Alumel thermocouples were placed in each specimen, at the interface between the porcelain tube and concrete, one near the top and one near the bottom. Two more thermocouples were located similarly on the outside surface and were held in place with sealing wax. Before

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FIGURE 3. THERMAL-STRESS APPARATUS

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testing, a plastic film* was sprayed on each specimen to make the surface water resistant.

The results of thermal-stress tests on cylindrical concrete specimens of both large and small outside diameters are shown in Table 4. The values for "Calculated Outer Surface Tensile Stress" were obtained by use of the formula for the thermal stress on the outer surface of a thick-walled, hollow cylinder⁽³⁾:

$$S_t = \frac{\Delta T \alpha E}{2(1 - \nu) \log \frac{c}{b}} \left(\frac{2b^2}{1 - c^2} - b^2 \log \frac{c}{b} \right)$$

where

S_t = tensile stress

α = coefficient of thermal expansion

E = modulus of elasticity

ν = Poisson's ratio

c = outer radius

b = inner radius

ΔT = temperature differential

The calculated values for the tensile stresses at the surfaces greatly exceeded tensile strength values reported for concrete. These stresses were concentrated at the surface, however, and the development of very fine surface cracks may have been sufficient to relieve a considerable amount of tension without rendering the concrete unsound.

Only one of the concrete specimens developed cracks when subjected to a steady thermal stress. As many as 4 cycles were required to produce cracking by a cyclic thermal stress. Cracks which developed on cyclic

* Krylon plastic spray.

TABLE 4. RESULTS OF THERMAL STRESS TESTS ON LIMONITE-IRON HIGH-DENSITY CONCRETE

Specimen Number	Type of Limonite	Dimensions of Cylinder	Maximum Internal Temperature, °F.	Maximum Temperature Differential, °F.	Duration of Test, Hrs.	Calculated* Outer Surface Tensile Stress, p.s.i.	Remarks
5308-64	Alabama ore	3-1/2"D x 7"	260	170	5	2060	No cracks
5308-69A	Ditto	6"D x 7"	220	190	1-1/2	2300	No cracks
"	"	"	400	360	12 4 cycles	4380	Faint cracks developed
5308-69B	"	"	450	380	7 3 cycles	4620	Fine cracks developed
"	"	"	"	"	6 additional hours, 3 cycles	"	No more cracks
5308-62A	"	3-1/2"D x 7"	400	250 (estimated)	3-3/4	3000	Faint cracks
5308-62B	"	"	320	150	3-1/2	1820	No cracks
5308-73A	James Mine ore	"	250	180	10	2180	No cracks

* In these calculations, a value of 5.1×10^6 p.s.i. was used for the modulus of elasticity, and a value of 7×10^{-6} inches/inch/°F. was used for the coefficient of thermal expansion. A value of 0.3 was assumed for Poisson's ratio.

stressing were not propagated further by additional cycling. The tests indicate that a limonite-iron, high-density concrete can withstand a thermal stress which will produce a calculated surface tensile stress of nearly 3000 p.s.i. without any deterioration. Much more severe stress can be withstood without producing more than minor surface damage to the concrete.

Thermal Conductivity

The thermal conductivity of limonite-iron high-density concrete was determined with apparatus previously developed at Battelle. The method consisted of maintaining a constant elevated temperature on one side of a concrete slab and cooling the other side, while observing the temperature differential across the thickness and measuring the heat flow per unit area. A general view of the apparatus is shown in Figure 5, and a schematic diagram is shown in Figure 6.

The elevated temperature was maintained by warm air recirculated, by means of a fan, across space heaters located in the upper chamber. The temperature was controlled by control thermocouples (twenty elements in series) actuating a Foxboro controller. The differential temperature across the specimen was determined at five points within an 8-inch square cross section in the middle of the slab. The temperatures were measured by Number 36-gauge copper-constantan thermocouples embedded in the surfaces of the slab with Portland cement.

The slab of concrete was 18 inches square and 3 inches thick. Guard blocks of the same material surrounded the slab and gave an over-

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FIGURE 5. THERMAL-CONDUCTIVITY APPARATUS

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FIGURE 6. SCHEMATIC DIAGRAM OF THERMAL - CONDUCTIVITY APPARATUS

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all area of 36 square inches. The slab had cured for a period of four months at 80°F. and 50 per cent relative humidity before being tested.

The rate of heat flow was measured by means of an 8-inch-square heat-flow meter centrally located between the test slab and a water-cooled plate at constant temperature. The heat-flow meter was calibrated in a guarded hot-plate apparatus with two guarded hot plates similar to the one described by M. S. Van Dusen⁽⁴⁾.

The thermal-conductivity values obtained for the test specimen at six equilibrium states and at several different mean temperatures are given in Figure 7. A steady decrease in thermal conductivity took place with each succeeding test, apparently due to a drying action taking place in the concrete. Lack of time prohibited further checking on this phenomenon.

Alabama limonite was used in the preparation of the test slab. Another test slab containing James Mine ore was also prepared, but time did not permit its use in this test.

Heat Liberation (Adiabatic Temperature Rise During Setting)

In the casting of large concrete masses, it is often necessary to cool the mass or to provide sufficient time between placing successive pours to eliminate the heat released by the setting of the cement. Cracking of the concrete will result if this precaution is not taken. The amount of heat liberated and the resultant temperature rise of the concrete is a function of the type and amount of cement used in the concrete and of the shape and size of the casting, as well as the ambient

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FIGURE 7. THERMAL CONDUCTIVITY VERSUS TEMPERATURE FOR LIMONITE-IRON CONCRETE

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air conditions. If the temperature rise experienced by the concrete under adiabatic conditions (no heat loss) is known, the temperature rise which will occur in a given mass under given ambient conditions can be calculated by well-known heat-transfer relations. A test was designed to provide information on the adiabatic temperature rise of limonite-iron concrete. The apparatus was similar to that used by the Bureau of Reclamation for determining the specific heat of concretes⁽⁵⁾. A photograph of this apparatus is shown in Figure 8, and a schematic diagram is shown in Figure 9.

The procedure followed in this test consisted of the following operations. A freshly mixed batch of concrete was cast into a galvanized iron can 3-1/2 inches in diameter and 4 inches in height. Two 24-gauge Chromel-Alumel thermocouples were embedded in the fresh concrete, one in the center and one near the wall. A third thermocouple was soldered on the outside wall of the can. The can containing the concrete was placed inside another metal container, from which it was separated by a 1-inch dead-air space. A fourth thermocouple was soldered to the inside wall of the container surrounding the dead-air space. Adiabatic conditions were obtained by maintaining a zero temperature drop across the dead-air space surrounding the concrete during the setting period. This was done by controlling the temperature of air circulated around the assembly; the air was heated by passage over resistance coils and the current input to these coils was manually adjusted. The temperature of the circulating air was recorded by a Foxboro temperature recorder.

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FIGURE 8. HEAT-LIBERATION APPARATUS

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FIGURE 9. SCHEMATIC DRAWING OF HEAT-LIBERATION APPARATUS

Two preliminary test runs on limonite-iron high-density concrete were conducted to obtain a rough approximation to the time-temperature relation so as to determine when the apparatus required more frequent readings and power adjustments. After the preliminary test runs were made, three more tests were made on high-density concrete containing James Mine ore and two tests were made on high-density concrete containing Alabama limonite. The temperature rise was measured for a minimum of 56 hours, after which no measurable rise in temperature was observed. A supplementary test on the adiabatic temperature rise of neat Portland cement gave a value of greater than 110°F. in 16 hours.

The temperature rise during setting of high-density concretes at various times during the tests is shown in Table 5. The average maximum temperature rise of limonite-iron high-density concrete was about 40°F. The most significant rise took place within the first 48 hours after casting.

Effect of Temperature and Relative Humidity on
Equilibrium Water Content

The equilibrium water content of limonite-iron high-density concrete was determined at temperatures of 75°F. and 150°F., and at relative humidities of 10, 50, and 100 per cent. The method used in these determinations is similar to a method used by Powers and Brownyard⁽⁶⁾. A photograph of the apparatus is shown in Figure 10 and a schematic diagram is shown in Figure 11.

Essentially, the procedure consisted in passing air at a known temperature and humidity over powdered concrete samples until they came

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TABLE 5. ADIABATIC TEMPERATURE RISE OF LIMONITE-
IRON HIGH-DENSITY CONCRETES

Specimen Number	Type of Limonite	Temperature Rise, °F.		
		After 24 hrs.	After 48 hrs.	Maximum
1	Alabama ore	31	39	39
2	Ditto	28	34	34
3	"	19	42	42
4	James Mine ore	23	35	36
5	Ditto	27	39	43

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FIGURE 10. APPARATUS FOR DETERMINING EQUILIBRIUM WATER CONTENT VERSUS RELATIVE HUMIDITY ISOTHERMS

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Oven top view

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FIGURE II. SCHEMATIC DRAWING OF APPARATUS FOR DETERMINING EQUILIBRIUM WATER CONTENT VERSUS RELATIVE HUMIDITY

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to constant weight and determining the water content of the concrete by ignition. Compressed air was dried completely and stripped of its CO_2 content by passage through a train of NaOH solution, concentrated H_2SO_4 , and Ascarite*. It was then humidified to nearly the desired humidity by passage through a H_2SO_4 solution and was passed into the oven where it was heated to oven temperature by passing through copper coils before bubbling through two more wash bottles. The last two wash bottles contained sulfuric acid adjusted to a concentration that gave the air the correct water vapor pressure. The air with the adjusted water content passed from the last wash bottle to the sample tubes containing powdered concrete.

The concrete used in this test was taken from cured specimens used in the heat-liberation tests. After the concrete was crushed, the punchings were removed, and the remaining mortar was ground to pass through a 70-mesh sieve. The powdered test samples were held in the sample tubes between porous plugs of glass wool.

During the tests, the sample tubes were removed from the oven at approximately one day-intervals and weighed. Approximately two weeks were required for the samples to come to constant weight under each set of test conditions. After the equilibrium weights were determined for all three points on each isotherm, the samples were transferred to porcelain crucibles and ignited. The equilibrium water contents were thus determined. The results of the tests and the calculated water content of the concrete as a function of temperature and humidity are given in Table 6.

* A commercial CO_2 adsorbent: asbestos impregnated with NaOH.

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TABLE 6. EQUILIBRIUM WATER CONTENT OF LIMONITE-IRON CONCRETE

Relative Humidity, Per Cent	Equilibrium Water Content, Pounds of H ₂ O/Pound of Dry Solids			
	Powdered Test Samples*		Limonite-Iron Concrete**	
	75°F.	150°F.	75°F.	150°F.
10	0.141	0.097	0.058	0.040
45	0.157	0.100	0.064	0.041
100	0.178	0.109	0.073	0.044

* The punchings were removed from concrete in the preparation of these samples.

** Calculated for original concrete on basis of values measured for samples with no punchings.

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Gas Permeability

Prepared by J. K. Thompson and A. D. Schwoppe

In contrast to flow nozzles and orifices, porous materials generally possess a linear relationship between fluid flow and pressure differential. In general, the concrete and cement specimens tested conformed to this characteristic. This relationship is expressed by a modification of Darcy's law for low-velocity flow, first found empirically from experiments with flow through beds of sand:

$$\frac{dq}{dt} \frac{1}{A} = \frac{K}{\mu} \frac{\Delta P}{L} \quad (1)$$

where

$\frac{dq}{dt}$ = weight rate of efflux, pound per second

A = area of the porous medium, square inch

ΔP = drop in pressure across the thickness of the medium,
p.s.i.

L = thickness of the medium, feet

K = coefficient of permeability of the medium, pound per
second per second

μ = viscosity of fluid, pound per foot-second
(0.000672 x centipoises)

Flow versus pressure differential was determined experimentally for specimens of neat Portland cement, Portland cement plus limonite fine aggregate, and Portland cement plus limonite fine aggregate plus steel punchings (coarse aggregate). From the data thus obtained, the coefficients of permeability were computed. The tests were conducted using

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oxygen as the fluid at pressure differentials up to 50 p.s.i. above atmospheric pressure and at room temperature.

The tests were carried out on plugs of cement and concrete cast in short pipe sections. The specimens of Portland cement and Portland cement plus limonite fine aggregate were cast in 1/2-inch, 1-inch, and 2-inch thicknesses in 2-inch (diameter) pipe. The specimens of Portland cement plus limonite plus steel punchings were cast in 3-inch, 6-inch, and 9-inch thicknesses in 5-inch pipe. The latter mixture was cast with two different orientations of the circular punchings.

Oxygen was supplied from a commercial cylinder, and flow was controlled by means of the attached regulator. Rate of flow was measured with suitable rotameters connected in the line from the supply tank to the pipe section containing the concrete specimen under test. Piping from the rotameter to the specimen was kept as short as possible, but maintaining laminar flow, and all joints were sealed and checked during the tests. Fore-pressure on the specimen was measured and adjusted by use of a Bourdon-tube-type pressure gauge mounted in the pipe wall at a suitable distance from the concrete. The oxygen was exhausted to the atmosphere through the specimen.

The average coefficients of permeability calculated from the test data for the specimens of Portland cement plus limonite fine aggregate and of Portland cement plus limonite fine aggregate plus steel punchings (coarse aggregate) oriented randomly are shown in Table 7. The gas flow permitted by the specimens of neat Portland cement and of the concrete containing punchings oriented with their flat surfaces perpendicular to

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TABLE 7. AVERAGE COEFFICIENTS OF PERMEABILITY* OF
CONCRETE SPECIMENS

For Pressure-Differential Range 0 to 50 p.s.i.g.

Specimen No.	Thickness, Inches	Coefficient of Permeability (K)*
<u>Portland Cement + Fine Limonite (Alabama) + Punchings**</u>		
CA-1	3	34***
<u>Portland Cement + Fine Limonite (James Mine) + Punchings**</u>		
CA-2	3	113
CA-3	6	2.8
CA-4	9	8.1
<u>Portland Cement + Fine Limonite (James Mine)</u>		
A-8 & A-9	1/2	22.7
A-10	1	9.0
A-11	1	18.9
A-12 & A-13	1	6.0

* Calculated using Equation (1), page 34. Units are pound
per second per second x 10^{-13} .

** Oriented randomly.

*** K = 25.5 after three months.

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the direction of flow was too small to be measurable with the flowmeters available. The coefficients of permeability in Table 7 apply to the pressure differential range of 0 to 50 p.s.i. above atmospheric and with the gas at room temperature. The specimens were tested about a month after being cast.

Although there is considerable overlapping of the permeability ranges of the fine and coarse aggregate concretes indicated by the tests, it appears that the addition of properly oriented coarse aggregate increases the gas permeability of the concrete. This effect was also found by other investigators⁽⁷⁾.

However, since the steel punchings are flat disks, their average orientation in the concrete would be expected to influence the permeability. This appears to be true, since the results of tests of specimens with the faces of the disks perpendicular to the direction of flow indicate that the permeability is so small as to be unmeasurable with available equipment. Apparently, the effect of blocking flow passages is greater for this orientation than the increase in permeability due to expansion of the cement away from the punchings as the concrete hardens.

It may be noted from Darcy's law that the rate of flow for the same pressure differential is inversely proportional to the thickness of the media in the direction of flow. The apparent deviation of the results of these tests from this law may be due to the fact that the thicker specimens require a longer time to dry out after casting than the relatively thin ones.

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It has been observed from tests of the same specimens at different times that the permeability increases somewhat as the concrete ages. After a certain length of time, however, the permeability approaches a constant value. An example of this is shown in Figure 12 for the coarse-aggregate concrete tested. The water-content ratio seems to have an effect on the permeability of the hardened concrete, and thus the permeability is dependent on pouring condition, as well as proportion of dry constituents.

The cause of the distinct bend in the curves of Figure 12 has not been determined, but it was shown that it was not caused by the development of a leak in the system. The flow data were reproducible, and the bend occurs at an approximately constant value of rate of flow. The possibility that velocity of the gas flowing past the pressure-gauge tap was affecting the pressure readings for this specimen and others was ruled out by a suitable test. A pitot tube was mounted in the pipe wall downstream from the static-pressure gauge with the mouth of the tube adjacent to the static-pressure tap. A flow test was made, up to 50 p.s.i. pressure differential, without obtaining any difference between the static and total-pressure readings. A similar change in permeability at higher pressures was observed with the plain limonite concrete.

The application of heat to the cement or concrete increases its gas permeability considerably and permanently. A group of tests was conducted on a 3-inch-thick specimen (CA-1) of the limonite concrete containing steel punchings to determine the effect on permeability of increasing the entering-gas temperature from 20°C. to 100°C.

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FIGURE 12. FLOW OF OXYGEN VERSUS PRESSURE DIFFERENTIAL, SPECIMEN CA-1, 3-INCH THICK AT VARIOUS TIMES AFTER CASTING

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In these tests, the oxygen was heated by a tube furnace as it entered the pipe section containing the concrete specimen. The gas temperature at the inside surface of the concrete and at the pressure-gauge tap was measured with thermocouples mounted in the pipe wall. The temperature was controlled by means of a Variac (variable autotransformer) connected in the furnace circuit. Temperature of the gas leaving the concrete was measured with a thermometer.

The results obtained are plotted in Figure 13. The values in this figure represent a more or less permanent increase in the permeability of the concrete as the entering-gas temperature is increased. Flow readings taken at 20°, 55°, 85°, 100°C., and at $\Delta P = 30$ p.s.i. indicate that increase in permeability is directly proportional to the temperature to which the concrete is subjected in this temperature range. Time at temperature will also cause some further increase in the permeability.

The permanent effect of the heated gas on the permeability of the concrete is shown by the fourth curve in Figure 12. Very little difference in flow versus pressure was observed with the gas at 100°C. and with the gas at room temperature after the concrete had cooled. The coefficient of permeability of this concrete (Specimen CA-1) was thus increased to 34 pounds per second per second times 10^{-13} .

Mechanical Properties

Data on the mechanical properties of limonite-iron high-density concrete are presented in this section. Some scattered data also are

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FIGURE 13. FLOW OF OXYGEN PERMITTED BY CONCRETE SPECIMEN CA-1, HARDENED AT ROOM TEMPERATURE AND SUBJECTED TO INCREASING INLET GAS TEMPERATURE

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given for M.O. concrete, Portland high-density concrete containing punchings and steel shot, and plain concrete. Details on their composition and the materials used in these concretes are given in the Appendix.

Dimensional Stability

The effect of storage on the dimensional stability of high-density concrete was determined by measuring the linear change of 3- by 3- by 10- inch specimens at periodic intervals. Linear-change measurements were made on limonite-iron concrete and concrete containing punchings and steel shot (no limonite), both stored at 80°F. in damp sand.

No linear change took place in any of the specimens until after one month of storage. The linear expansion of limonite-iron high-density concrete was 0.04 per cent at the end of two months and 0.07 per cent at the end of six months. The linear change of high-density concrete containing punchings and steel shot was 0.02 per cent at the end of two months.

Compressive Strength

The compressive strength of high-density concrete was determined by applying a constantly increasing load to cast cylindrical specimens measuring 3 inches in diameter by 6 inches in height until complete failure. A seventy-five-thousand-pound-capacity Baldwin and Southwark testing machine supplied the load. About one hour before testing, each specimen was capped with plaster of Paris. Strain gauges were mounted on the sides of each specimen.

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Compressive-strength data were obtained on limonite-iron high-density concrete, M.O. concrete, and an all-iron-aggregate concrete. Tests were made at the end of 7 days' and 28 days' storage on the majority of these concretes. The results are shown in Table 8. Except as indicated, each value is the average for three test specimens. The M.O. concretes and two batches of limonite-iron concrete were stored at 80°F. and 50 per cent relative humidity before testing. The rest were stored in damp sand at 80°F. before testing.

Limonite-iron high-density concrete had the highest compressive strength of all of the concretes tested. The high-density concrete containing James Mine ore had a slightly higher compressive strength than the concrete containing Alabama ore. Concrete prepared with M.O. cement was not so strong as concrete prepared with Portland cement and decreased in strength with age. The decrease was less pronounced in concrete specimens containing Calgon (sodium hexametaphosphate) and in which the steel punchings had been phosphated.

Modulus of Elasticity

The stress-strain relationship of high-density concrete in compression was determined in conjunction with the determination of compressive strength. Two SR-4, A1 strain gauges were mounted on the sides of each of the 3-inch-diameter by 6-inch cylindrical compression specimens at least 24 hours before testing. Load and strain readings were taken simultaneously during the application of continuous load up to the breaking point. The stress was calculated by dividing the total load by the cross-

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TABLE 8. COMPRESSIVE STRENGTHS OF HIGH-DENSITY CONCRETES
AFTER 7 DAYS' AND 28 DAYS' STORAGE

Description	Storage Conditions, % R.H.	Compressive Strength, p.s.i.	
		7 Days	28 Days
M.O. concrete (plus Galgon)	50	3170	1750
M.O. concrete (no Calgon) with phosphated punchings	50	3040	Not suitable for testing
M.O. concrete (plus Calgon) with phosphated punchings	50	3850	2810
P.C. high-density concrete with punchings and steel shot	Damp sand	2900	—
Limonite-iron high-density concrete with Alabama limonite ore	Damp sand	4730*	4330
Limonite-iron high-density concrete with Alabama limonite ore	50	3550	4070
Limonite-iron high-density concrete with James Mine ore	50	4660	—

* Average value for six cylinders.

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sectional area of the specimen. For each determination, a minimum of three specimens, each containing two strain gauges, were tested; the reported values are the average of the six measurements.

Stress-strain curves were plotted for each specimen and were found to deviate considerable from a straight line. Since the slope of the curve was not a constant, the modulus of elasticity varied with the applied stress. Representative stress-strain curves are given for M.O. concretes in Figure 14, and for limonite-iron high-density concretes in Figure 15.

The modulus may be reported in several different ways⁽⁸⁾. The values reported in Table 9 are for the secant modulus at a stress of 2000 pounds per square inch; i.e., the slope of a line drawn from the origin to a stress of 2000 pounds per square inch.

Up to a stress of about 2000 pounds per square inch, the modulus of elasticity was about the same for both M.O. concrete and limonite-iron high-density concrete. Above this stress, the modulus was considerably lower for M.O. concrete than for the limonite-iron concrete.

Flexural Strength

The flexural strength of high-density concrete was determined by the method reported in A.S.T.M. Test Number C78. Cast bricks of the concrete, 3 inch by 3 inch by 10 inch, were loaded at one-third points of a 9-inch span. They were loaded and supported to prevent restraint. The load was supplied by a 20,000-pound-capacity Baldwin and Southwark testing machine. The modulus of rupture was calculated by the following formula:

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FIGURE 14. STRESS-STRAIN RELATIONSHIPS OF
M.O. CONCRETES

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FIGURE 15. STRESS-STRAIN RELATIONSHIPS OF LIMONITE-IRON, HIGH-DENSITY CONCRETES

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TABLE 9. COMPRESSIONAL MODULUS OF ELASTICITY OF HIGH-DENSITY
CONCRETES AFTER 7 DAYS' STORAGE

Description	Storage Conditions, % R.H.	Modulus of Elasticity, p.s.i. x 10 ⁻⁶	
		7 Days	25 Days
M.O. concrete (plus Calgon)	50	5.4	—
M.O. concrete (no Calgon) with phosphated punchings	50	8.7	Not suitable for testing
M.O. concrete (plus Calgon) with phosphated punchings	50	6.2	3.4
P.C. high-density concrete with punchings and steel shot	Damp sand	4.4	—
Limonite-iron high-density concrete with Alabama limonite ore	Damp sand	7.4	7.4
Limonite-iron high-density concrete with Alabama limonite ore	50	5.6	3.4
Limonite-iron high-density concrete with James Mine ore	50	5.1	—

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TABLE 10. FLEXURAL STRENGTH OF LIMONITE-IRON,
HIGH-DENSITY CONCRETE

Description	Modulus of Rupture, p.s.i.	
	7 Days	28 Days
Limonite-iron high-density concrete containing Alabama limonite	867	966
P.C. high-density concrete containing punchings and steel shot	616	—
Ordinary Portland cement concrete*	400	600

* These values were taken from Reference 9.

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Bonding Strength

The bonding strength between high-density concrete and steel was determined in a manner similar to that described by Duff Abrams⁽¹⁰⁾. A simplified drawing of the test setup is shown in Figure 16. The concrete cylinder rested on the stationary head of a 20,000-pound-capacity Baldwin and Southwark testing machine. A 1/2-inch-diameter hot-rolled, steel bar was embedded axially in a 3-1/2-inch-diameter by 7-inch concrete cylinder. The lower movable head of the testing machine gripped the bar and caused a force acting downward. The slip of the bar was measured directly by an Ames dial gauge supported on the top of the cylinder.

Pull-out tests were made on M.O. concrete, limonite-iron concrete, and plain concrete. Stress-slip* curves after 7 days' storage are shown in Figure 17; stress-slip curves after 28 days' storage are shown in Figure 18.

The measurement of the actual bond between concrete and steel is a difficult task and a simple satisfactory method has not yet been reported. The actual bonding strength between concrete and steel cannot be calculated from the curves presented here; however, a comparison of the relative bond strength of various concretes can be made from their load-slip curves. It is evident that the bond between limonite-iron concrete and steel should be adequate. The cohesive stresses developed between steel and limonite-iron concrete were higher than the stresses developed between steel and plain concrete by as much as 100 pounds per square inch.

* The stress was calculated by the following equation: $S = \frac{L}{\pi dh}$, where L = total load applied to the specimen, d = diameter of the steel bar, and h = depth of embedment.

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FIGURE 16. GENERAL VIEW OF PULL-OUT TEST

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FIGURE 17. STRESS-SLIP CURVES FOR HIGH-DENSITY CONCRETES AFTER 7 DAYS' STORAGE

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FIGURE 18. STRESS-SLIP CURVES FOR HIGH - DENSITY CONCRETES AFTER 28 DAYS' STORAGE

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It may also be noted that the bonding strength was greater for the limonite-iron concrete stored in damp sand than that for the same concrete stored at 50 per cent relative humidity. The bonding strength of M.O. concrete was low.

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APPENDIX

Materials Used

Iron Punchings: Aminco iron punchings were used as the coarse aggregate. Their average dimension were 1-inch diameter by 1/4 inch thick.

Limonite (Fine Aggregate): The James Mine ore was supplied by the Pickands Mather Mining Company, Cleveland, Ohio, and the Alabama limonite was supplied by the Shook and Fletcher Supply Company, Birmingham, Alabama. Both ores were prepared to meet the following requirements:

<u>U.S. Screen Size</u>	<u>Per Cent Passing</u>
4	90-100
10	65-75
20	35-55
40	25-35
65	15-25
100	5-15

Fine Iron Shot: Chilled iron shot from Globe Steel Abrasive Company, Mansfield, Ohio, SAE Size 330, 100 per cent passing through a 16-mesh Tyler screen and retained on a 24-mesh Tyler screen.

Coarse Iron Shot: Chilled iron shot from Globe Steel Abrasive Company, Mansfield, Ohio, SAE Size 1320, 100 per cent passing through a 4-mesh Tyler screen and retained on a 7-mesh Tyler screen.

Portland Cement: Miami brand Portland cement, Type I.

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Plastiment: Proprietary material for increasing workability of concrete. Supplied by Sika Chemical Corporation, Passaic, New Jersey.

Magnesium Oxide: Westvaco 35-Hour magnesia from Westvaco Chemical Division, New York, New York.

Magnesium Chloride: Commercial-grade magnesium chloride from Dow Chemical Company, Midland, Michigan.

Calgon: Adjusted RS Calgon from Calgon, Inc., Pittsburgh, Pennsylvania.

Preparation of Specimens

The majority of the specimens tested in this program were fabricated in a room maintained at a temperature of 80°F. and a relative humidity of approximately 50 per cent. The batching was done in a one-half-cubic-yard, power-driven, concrete mixer. The fresh concrete was poured into molds and tamped and vibrated at 2400 vpm. The period of vibration varied from 45 seconds to 3 minutes, depending upon the size and shape of the specimen molds.

The limonite-iron high-density concrete was prepared with the following batch composition:

<u>Ingredient</u>	<u>Weight Per Cent</u>
Portland cement	13.0
Limonite	26.0
Punchings	56.7
Plastiment	0.21
Water	4.1

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The Portland concrete containing punchings and steel shot had the following batch composition:

<u>Ingredient</u>	<u>Weight Per Cent</u>
Portland cement	11.6
SAE 1320 shot	21.9
SAE 330 shot	14.6
Punchings	48.4
Water	3.5

The M.O. concretes had the following general composition:

<u>Ingredient</u>	<u>Weight Per Cent</u>
Punchings	53
SAE 1320 steel shot	24
SAE 330 steel shot	16
Magnesia	7

Calgon 1 per cent by weight of dry MgO

26° Bé $MgCl_2$ solution . 625 cc. per 700 grams of MgO

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