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THERMAL CONDUCTIVITY OF A RECENTLY DEVELOPED LIGHTWEIGHT STRUCTURAL CONCRETE

REFERENCE: Van Geem, M.G., "**Thermal Conductivity Of a Recently Developed Lightweight Structural Concrete,**" Proceedings of First California Thermal Insulation International Conference, BHF&TI (01-88), S.A. Siddiqui, Editor, Bureau of Home Furnishings and Thermal Insulation, North Highlands, California, 1988, pp. 108-127.

ABSTRACT: A lightweight structural concrete was developed for use in exterior walls of low-rise residential and commercial buildings. The lightweight concrete has a unit weight of 800 kg/m^3 (50 pcf), a compressive strength of 13.8 MPa (2000 psi), and a thermal conductivity of 0.23 W/m•K (1.6 Btu•in./hr•ft^2•°F). Lightweight concretes have not been previously developed with this combination of low density and moderate strength. The most commonly used concrete, normal weight concrete, has a unit weight of approximately 2320 kg/m^3 (145 pcf), a compressive strength in the range of 17 to 41 MPa (2500 to 6000 psi), and a thermal conductivity of 1.7 to 2.3 W/m•K (12 to 16 Btu•in./hr•ft^2•°F).

Thermal conductivity of the newly developed concrete was measured using three test methods. A calibrated hot box (ASTM Designation: C976) was used to measure thermal conductivity of an 8-in. thick, full-size wall assembly. Thermal conductivity of small concrete sections was measured using two methods: a guarded hot plate (ASTM Designation: C177) and heat flux transducers (ASTM Designation: C1046).

Thermal conductivity of normal weight concrete was measured for comparison. The newly developed structural lightweight concrete has 1/9th the thermal conductivity of normal weight concrete and can be used to combine the structural, thermal insulation, and heat storage capacity functions of exterior walls in one element.

KEY WORDS: calibrated hot box, energy, heat transmission, lightweight concrete, structural concrete, thermal conductivity, thermal mass, thermal resistance

INTRODUCTION

A lightweight structural concrete was developed for use in exterior walls of low-rise residential and commercial buildings. The lightweight concrete has a unit weight of 800 kg/m^3 (50 pcf), a compressive strength of 13.8 MPa (2000 psi), and a thermal conductivity of 0.23 W/m•k (1.6 Btu•in./hr•ft^2•°F). Lightweight concretes have not been previously developed with this combination of low density and moderate strength. The most commonly used concrete, normal weight concrete, has a unit weight of approximately 2320 kg/m^3 (145 pcf), a compressive strength in the range of 17 to 41 Mpa (2500 to 6000 psi), and thermal conductivity of 1.7 to 2.3 W/m•k (12 to 16 Btu•in./hr•ft^2•°F).

Although it is envisioned that the newly developed concrete could be used for many building components, project emphasis was to evaluate the concrete for use in exterior walls for low-rise buildings. The portland cement concrete developed for this project combines the structural, thermal insulation, and

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heat storage capacity functions of exterior walls in one element. For many climates this concrete can be used as a complete wall system in low-rise buildings without additional insulation.[1]

Project work is reported in References 1,2, and 3. Reference 1 is a feasibility study to identify uses for the proposed lightweight portland cement concrete in buildings. Reference 2 includes: (1) selection of materials and mix designs for the lightweight portland cement and lightweight polymer concretes, (2) physical and thermal properties of candidate concretes, and (3) casting and surface finishing techniques for the most desirable mixes. Reference 3 describes heat transfer measurements of full-size wall assemblies constructed of the developed portland cement concrete.

The program was conducted at Construction Technology Laboratories, Inc. (CTL). The project was sponsored jointly by the U.S. Department of Energy (DOE) Office of Buildings and Community Systems, and the Portland Cement Association. It is part of the Building Thermal Envelope Systems and Materials Program (BTESM), Energy Division, at Oak Ridge National Laboratory (ORNL).

CONCRETE MIX DEVELOPMENT

Portland cement concrete consists, essentially, of portland cement, aggregates, and water. Relatively small quantities of other materials are frequently included to enhance certain properties which may be desirable for specific applications. Generally, aggregate is between 60 and 75% and cement, water, and air between 25 and 40% of the concrete volume. Since aggregate volume is so high, its specific gravity greatly influences the weight of the concrete. While cement has the highest specific gravity, it occupies a relatively small volume. Since cement is the strength producing ingredient the amount that it can be reduce is limited.

Aggregates used to make concrete with a desired unit weight are available in a wide range of unit weights. Thermal conductivity of concrete is primarily dependent on its unit weight which is a function of the constituent aggregates used to make the concrete. To a lesser extent, thermal conductivity is dependent on the cement paste. Generally, concrete conductivity increases exponentially with unit weight. Concrete with a unit weight of 800 kg/m^3 (50 pcf) has a thermal conductivity of approximately 0.22 W/m•K (1.5 Btu•in./hr•ft^2•°F) while concrete with a unit weight of 2240 kg/m^3 (140 pcf) has a thermal conductivity of approximately 2.3 W/m•K (16 Btu•in./hr•ft^2•°F).

Based on the above, the investigative procedure consisted of locating the lightest available aggregates capable of producing concrete having sufficient structural capacity. With these aggregates, mixes were designed having the lowest cement contents (to lower weight) consistent with obtaining the required strength. Chemical and mineral admixtures were used to enhance the concrete's fresh properties and strength-to-weight relationship. (The strength-to-weight ratio is the ratio of the concrete's compressive strength to its unit weight or density.)

More than 25 preliminary concrete mixes were made using seven aggregates, singly or in combination. Mixes utilizing 3M Macrolite™ as an aggregate had the highest strength-to-weight ratio and had the best chance of meeting the program objectives. Therefore, mixes were made with this aggregate to optimize the strength-to-weight relationship and to provide test specimens for further testing.

Macrolite Ceramic Spheres, shown in Fig. 1, is a recently developed ceramic supplied by the 3M Company of St. Paul, Minnesota. A unique feature of this aggregate is that it has a relatively low water absorption of less than 0.5%. Typical low-absorption lightweight aggregates have absorptions ranging from 6 to 14%. The aggregate was supplied in two sizes; 12.7 to 4.75 mm (1/2 in. to No. 4) and 4.75 mm to 0.30 mm (No. 4 to No. 50). Aggregate sizes are described by sieve opening sizes according to ASTM Designation: E11, "Standard Specification for Wire-Cloth Sieves for Testing Purposes."

Fillite was added to the concrete mix to provide a very fine lightweight material. It is furnished by Fillite USA, Inc., of Huntington, West Virginia, and is described as hollow alumina silica microspheres. The particles are similar in size and chemical composition to fly ash. However, they are hollow and have a much lower specific gravity than most fly ash. The Fillite size range was 30 to 0.30 mm.

The final mix design is shown in Table 1. It was used for determining various concrete physical and thermal properties and for casting two full-size wall panels, designated Walls L and S, for determination of thermal properties. The same volumetric mix design was used for both panels. However, aggregate weights varied because of the differences in specific gravities of aggregates from different shipments. The amount of vinsol resin air entraining agent was varied slightly to obtain a concrete unit weight of about 800 kg/m^3 (50 pcf).

PHYSICAL AND THERMAL PROPERTIES OF SMALL-SCALE SPECIMENS

Selected physical and thermal properties were measured on specimens cast from six concrete mixes using 3M Macrolite as aggregates. The six mixes were similar to that presented in Table 1. Test results are summarized in Table 2. Reference 2 gives details of specimen preparations and test procedures.

Reference 2 also compares properties of the newly developed concrete to properties of conventional normal weight and lightweight concretes.

FULL-SIZE TEST SPECIMENS

Two lightweight structural concrete walls were constructed by CTL and subsequently tested in a calibrated hot box. Walls were cast horizontally and have overall nominal dimensions of 2.62x2.62 m (103x103 in.).

Wall Construction

Wall L is a lightweight structural concrete wall with an average thickness of 203 mm (8.00 in.). Wall S is similar to Wall L except for a 150 mm (6 in.) high normal weight concrete strip running horizontally across the wall at mid-height. The horizontal strip simulates a floor slab extending through an exterior wall. Average thickness of Wall S is 206 mm (8.13 in.).

The concrete mix for Walls L and S is presented in Table 1. Reinforcement representative of actual wall construction was placed within Walls L and S. Reinforcement consisted of a single layer of 13-mm (No. 4) bars spaced 305 mm (12 in.) center-to-center in each direction. The reinforcement was located at the walls' approximate mid-thickness.

Walls L and S were allowed to cure in the formwork for approximately 2 weeks. After removing from formwork, Wall L was allowed to air dry in the laboratory at a temperature of 18±6°C (65±10°F) for approximately 3 months. Wall S was air dried in the laboratory at a temperature of 21±6°C (70±10°F) for approximately 4 months.

Prior to testing, the faces of Walls L and S were coated with a cementitious waterproofing material to seal minor surface imperfections. A textured, noncementitious paint was subsequently used as a finish coat. These coatings provided a white, uniform surface for both faces of each wall. Wall edges were left uncoated.

Measured weights, thicknesses, surface areas, and estimated moisture contents of Walls L and S are summarized in Table 3. Wall weights immediately before and after calibrated hot box tests are presented.

Reference 3 more fully describes wall construction.

Instrumentation

Eighty 20 gauge, Type T thermocouples, corresponding to ASTM Designation: E230, "Standard Temperature-Electromotive Force (EMF) Tables for Thermocouples," were used to measure temperatures during thermal testing. For each test wall, 16 thermocouples were located in the air space on each side of the test specimen, 16 on each face of the test wall, and 16 at the approximate concrete mid-thickness. The 16 thermocouples in each plane were spaced 525 mm (20-3/5 in.) apart in a 4x4 grid over the wall area.

An additional four thermocouples were located on each wall surface and at concrete mid-thickness along the centerline of the normal weight concrete strip of Wall S, as shown in Fig. 2.

Thermocouples measuring temperatures in the air space of each chamber of the calibrated hot box were located approximately 75 mm (3 in.) from the face of the test wall.

Surface thermocouples were securely attached to the wall with duct tape for a length of approximately 100 mm (4 in.). The tape covering the sensors was painted the same color as the test wall surface.

During wall construction, internal thermocouples were placed at wall mid-thickness on top of the first 100 mm (4 in.) concrete layer. To secure their location, thermocouples were taped to reinforcement or suspended by wire between reinforcement. The thermocouple junction was not placed in contact with the reinforcement. This was done for all internal thermocouples to avoid any influence by internal heat flow through reinforcement.

One heat flux transducer measuring 100x100 mm (4x4 in.) was mounted on each of the indoor and outdoor surfaces of the test walls. Sensors were located near the center of the walls as shown in Fig. 2. Heat flux transducers were calibrated using results from steady-state calibrated hot box tests on Wall L.

THERMAL PROPERTIES OF CONCRETE FOR STEADY-STATE TEMPERATURE CONDITIONS

Thermal resistances of Walls L and S were measured using a calibrated hot box. Thermal conductivity of the lightweight concrete portion of Wall S was measured using heat flux transducers. Thermal conductivities of specimens made from concrete mixes used to make Walls L and S were measured using a guarded hot plate.

Calibrated Hot Box Test Results

Heat flow through Walls L and S was measured under steady-state and dynamic temperature conditions. Results for dynamic temperature conditions are presented in Reference 3. Tests were conducted in the calibrated hot box facility shown in Figs. 3 and 4. Tests were performed in general accordance with ASTM Designation: C976, "Thermal Performance of Building Assemblies by Means of a Calibrated Hot Box."

Four calibrated hot box tests for steady-state temperature conditions were performed on each wall. Heat flow and temperature measurements were used to determine average overall thermal resistance (R_T) and thermal conductivity (k).

Steady-state results from calibrated hot box tests on Walls L and S are summarized in Table 4. Data are averages for 16 consecutive hours of testing. Wall mean temperature, heat flow, and overall thermal resistance are listed for each steady-state test condition applied to the walls. Thermal conductivity is listed only for the homogeneous specimen, Wall L.

The first column of Table 4 lists the wall mean temperature during each steady-state test. Wall mean temperature is determined from the average of the metering and climatic wall surface temperatures. Average temperatures for Wall S, with the normal weight concrete strip, are the area-weighted averages of the lightweight and normal weight concrete temperatures. Table 4 presents metering and climatic chamber air temperatures, and wall surface-to-surface temperature differentials.

Overall thermal resistances were calculated using heat flow measured by the calibrated hot box and surface resistance coefficients of 0.03 $m^2 \cdot K/W$ (0.17 $hr \cdot ft^2 \cdot {}^\circ F/Btu$) for outdoor air and 0.12 $m^2 \cdot K/W$ (0.68 $hr \cdot ft^2 \cdot {}^\circ F/Btu$) for indoor air.[5]

Thermal conductivity of Wall L and thermal resistances of Walls L and S at a specimen mean temperature of 24°C (75°F) were interpolated from measured values. Thermal conductivity of Wall L is 0.27 W/m•K (1.86 $Btu \cdot in./hr \cdot ft^2 \cdot {}^\circ F$) at 24°C (75°F). Overall thermal resistances of Walls L and S, respectively, are 0.92 and 0.83 $m^2 \cdot K/W$ (5.2 and 4.7 $hr \cdot ft^2 \cdot {}^\circ F/Btu$) at 24°C (75°F).

Thermal resistance of Wall S is 10% less than that for Wall L at 24°C (75°F). The normal weight concrete strip of Wall S is 5.8% of the total wall area.

Guarded Hot Plate Test Results

Thermal conductivities of specimens made from concrete mixes used to make Walls L and S were measured using a guarded hot plate. Tests were conducted at CTL in accordance with ASTM Designation: C177, "Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded Hot Plate," and ASTM Designation: C1045, "Calculating Thermal Transmission Properties from Steady-State Heat Flux Measurements."

Test Specimens

Two specimens were tested from the lightweight concrete for Wall L, the lightweight concrete for Wall S, and the normal weight concrete for Wall S. Nominal specimen dimensions were 50x300x300 mm (2x12x12 in.). Specimens were moist-cured at 23±1.7°C (73.4±3°F) and 100% RH for seven days, and then air-dried at 23±3°C (73±5°F) and 45±15% RH for 6 to 8 months. Specimens were ovendried before testing to eliminate effects of moisture migration during testing. Measured specimen dimensions and unit weights are given in Table 5.

Test Procedure

Test specimen temperatures are measured by chromel/alumel thermocouples embedded near the specimen surfaces. Thermocouples were placed in previously sawed grooves. Cement paste was used to fill the groove flush with the specimen surface and to secure thermocouples in place. Cement paste was also used to fill small holes in the specimen surface. The cement paste for lightweight concrete specimens had lightweight aggregate fines.

Embedded thermocouples reduce the effects of thermal contact resistance, which is due to the influence of any thin air gap between thermocouple wire and concrete. More information on embedding thermocouple wires and thermal contact resistance is given in Reference 6.

Test Results

Guarded hot plate test results are presented in Fig. 5 for Wall L and S lightweight concrete specimens and Fig. 6 for Wall S normal weight concrete specimens. Thermal conductivity is shown as a function of mean specimen temperature. Thermal conductivity increases with increasing mean temperature for lightweight concrete and decreases with increasing mean temperature for normal weight concrete. This result is consistent with available literature.[7]

Thermal conductivities at a specimen mean temperature of 24°C (75°F) were interpolated from measured guarded hot plate values. Thermal conductivities for Wall L, Wall S lightweight, and Wall S normal weight specimens, respectively, are 0.21, 0.21, and 1.82 W/m·K (1.43, 1.48, and 12.66 Btu·in./hr·ft^2·°F) at a specimen mean temperature of 24°C (75°F).

Average measured thermal conductivity of the lightweight concrete developed for this project is about 1/9th that for normal weight concrete.

Heat Flux Transducer Test Results

Two heat flux transducers (HFT's) were mounted on each wall specimen as shown in Fig. 2 and previously described in the "Instrumentation" section. Sensors were attached near the center of Wall L and on the lightweight concrete portion of Wall S.

Wall L calibrated hot box test results were used to calibrate the HFT's for Wall S. Heat flow through Wall S as measured by the HFT's was determined in accordance with ASTM Designation: C1046, "Standard Practice for In-Situ Measurement of Heat Flux and Temperature on Building Envelope Components."

Test Results

Heat flux transducer test results for the lightweight concrete portion of Wall S are presented in Fig. 5. Results are averages for 16 consecutive hours of testing during steady-state temperature conditions. Data were collected during steady-state calibrated hot box tests.

Results are similar for the heat flux transducers mounted on the climatic chamber and metering chamber sides of the wall.

Thermal conductivity of Wall S lightweight concrete at a mean specimen temperature of 24°C (75°F), interpolated from measured values, is 0.26 W/m•K (1.8 Btu•in./hr•ft^2•°F).

Discussion Of Results

Figure 5 presents thermal conductivities of the lightweight concrete measured by the calibrated hot box (ASTM: C976), the guarded hot plate (ASTM: C177), and heat flux transducers (ASTM: C1046). Thermal conductivities from calibrated hot box and HFT measurements are greater than those from guarded hot plate tests because guarded hot plate specimens were ovendried to remove moisture, while the wall specimens were air-dried. A 1% increase in specimen moisture content increases thermal conductivity 4 to 9%.[7,8]

Predicted thermal resistances of Walls L and S are presented in Table 6. Values are calculated using results from guarded hot plate tests on ovendry specimens and measured wall thicknesses. Calculation procedures are from the <u>ASHRAE Handbook - 1985 Fundamentals</u>.[5]

The predicted thermal resistance of Wall S is 17% less than that for Wall L. This compares to a 10% decrease in measured thermal resistance for Wall S compared to Wall L. A percent reduction comparison is used because predicted values are based on ovendry specimens and measured values are based on air-dried specimens.

A hot box round robin including results from 21 laboratories showed that measured values from the CTL calibrated hot box deviated in the range of 0 to 8% from expected values.[9]

SUMMARY AND CONCLUSIONS

This paper presents results of an investigation to develop a lightweight structural concrete with approximately 1/10th the thermal conductivity of normal weight concrete. Thermal and physical properties were measured on small-scale concrete specimens.

Heat transfer characteristics of two 200 mm (8 in.) thick, full-size wall assemblies were evaluated using a calibrated hot box, ASTM Designation: C976. One test specimen, designated Wall L., was a 200 mm (8 in.) thick wall constructed entirely of the newly developed lightweight structural concrete. The second specimen, designated Wall S, was the same as the first except for a 150 mm (6 in.) high normal weight concrete strip running horizontally across the wall at mid-height. The horizontal strip simulates a floor slab extending through an exterior wall.

The following conclusions are based on results obtained in this investigation.

- Thermal conductivity of Wall L, the homogeneous lightweight concrete wall, measured by the calibrated hot box (ASTM Designation: C976) is 0.27 W/m•K (1.86 Btu•in./hr•ft^2•°F). This value is for a specimen mean temperature of 24°C (75°F) and was interpolated from steady-state test results. The wall had an estimated moisture content of 2% based on ovendry unit weight.

- Overall thermal resistances of Walls L and S, respectively, interpolated from values measured using the calibrated hot box, are 0.92 and 0.83 m^2•K/W (5.2 and 4.7 hr•ft^2•°F/Btu) at 24°C (75°F). Thermal resistance of Wall S is 10% less than that for Wall L. The walls had estimated moisture contents of 2% based on ovendry unit weights.

- Thermal conductivities of small-scale lightweight and normal weight concrete specimens were measured using a guarded hot plate (ASTM Designation: C177). Thermal conductivities for Wall L lightweight, Wall S lightweight, and Wall S normal weight specimens, respectively, are 0.21, 0.21, and 1.82 W/m•K (1.43, 1.48, and 12.66 Btu•in./hr•ft^2•°F) at a specimen mean temperature of 24°C (75°F). Thermal conductivities at a specimen mean temperature of 24°C (75°F) were interpolated from steady-state test results. Guarded hot plate specimens were ovendried before testing.

- Thermal conductivity of a lightweight concrete portion of Wall S determined from heat flux transducers (ASTM Designation: C1046) was 0.26 W/m•K (1.8 Btu•in./hr•ft^2•°F). This value is for a specimen mean temperature of 24°C (75°F) and was interpolated from steady-state test results. The wall had an estimated moisture content of 2% based on ovendry unit weight.

- Predicted thermal resistances of Walls L and S were calculated using procedures from the ASHRAE Handbook - 1985 Fundamentals and measured thermal conductivities from guarded hot plate tests. Predicted thermal resistance of Wall S is 17% less than that for Wall L. This compares to a 10% decrease in measured thermal resistance for Wall S compared to Wall L. The reduction in R-value for Wall S is attributed to the normal weight concrete strip.

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Material	Quantities per 1.0 m^3 (Quantities per 1.0 cu yd)		
	Absolute Volume, m^3 (cu ft)	Weight, kg (lb)	
		Wall L	Wall S
Portland Cement	0.080 (2.16)	252 (425)	252 (425)
Silica Fume	0.012 (0.33)	26.1 (43)	26.1 (43)
Water	0.149 (4.01)	149 (250)	149 (250)
Air Content	0.060* (1.62)	--	--
3M Macrolite 12.7 to 4.75 mm (1/2" to #4)	0.342 (9.25)	174 (293)	195 (327)
4.75 to 0.30 mm (#4 to #50)	0.329 (8.88)	273 (459)	277 (466)
Fillite	0.028 (0.76)	20 (33)	20 (33)
Vinsol Resin, 2% Solution	1670-1950 ml (1275-1488 ml)	1.7 (2.81)	2.0 (3.28)
WRDA,** 4.55 ml/kg cement (7 oz/100 lb)	1160 ml (888 ml)	1.2 (1.96)	1.2 (1.96)

*Air content estimated at 6%.
**Water-reducing admixture manufactured by the Construction Products Division of W. R. Grace & Co.

Table 1 - Final Lightweight Portland Cement Concrete Mix Design

Property	Test Method	Pre-Test Curing	Measured Value
Unit Weight 28-day	ASTM: C567, as applicable	7 days 100% RH, 21 days 50±5% RH	793 kg/cu m (49.5 pcf)
Compressive Strength 7-day 28-day	ASTM: C39	7 days 100% RH 7 days 100% RH, 21 days 50±5% RH	11.5 MPa (1670 psi) 13.8 MPa (2000 psi)
Splitting Tensile Strength 7-day 28-day	ASTM: C496	7 days 100% RH 7 days 100% RH, 21 days 50±5% RH	1.3 MPa (185 psi) 0.9 MPa (135 psi)
Modulus of Rupture (Flexural Strength) 7-day 28-day	ASTM: C78	7 days 100% RH 7 days 100% RH, 21 days 50±5% RH	1.8 MPa (260 psi) 1.7 MPa (250 psi)
Shear Strength 7-day 28-day	See Reference 2	7 days 100% RH 7 days 100% RH, 21 days 50±5% RH	2.0 MPa (290 psi) 1.8 MPa (260 psi)
Modulus of Elasticity 28-day	ASTM: C469	7 days 100% RH, 21 days 50±5% RH	6400 MPa (0.93x10^6 psi)
Freezing and Thawing Resistance, relative dynamic modulus of elasticity	ASTM: C666, Procedure A (freezing in water)	7 days 100% RH, 21 days 50±5% RH, 24 hrs soaked in water	55% after 300 cycles
	See Reference 2 (freezing in air after 1/2 hr water soak)	14 days 100% RH, 14 days 50±5% RH	123% after 150 cycles
Drying Shrinkage @ 161 days @ 179 days @ 355 days	See Reference 2	7 days 100% RH, then 50±5% RH	0.088% 0.087% 0.093%
Thermal Conductivity	ASTM: C177* @ 75°F	7 days 100% RH, 58 to 70 days 45±15% RH, then ovendry	0.23 W/m•K (1.61 Btu•in./hr•sq ft•°F)
Specific Heat Saturated Surface Dry Air Dry	US Army Corps of Engineers CRD-C124-73 (Ref. 4)	100% RH	1060 J/kg•K (0.25 Btu/lb•°F) 460 J/kg•K (0.11 Btu/lb•°F)
Thermal Diffusivity	US Army Corps of Engineers CRD-C36-73 (Ref. 4)	100% RH	0.00096 sq m/hr (0.0104 sq ft/hr)
Coefficient of Thermal Expansion	Similar to ASTM: E228	7 days 100% RH, 42 to 46 days 45±15% RH	64x10^-6 mm/mm per °C (3.6x10^-6 in./in. per °F)

* Thermocouples for measuring specimen surface temperatures embedded flush with specimen surface.

Table 2 - Physical and Thermal Properties Hardened Lightweight Concrete

Property	Measured Value	
	Wall L	Wall S
Weight of Wall, kg (lb) Before testing	1250 (2760)	1320 (2910)
After testing	1240 (2720)	1310 (2890)
Unit Weight of Wall per Unit Surface Area of Wall,* kg/m^2 (lb/ft^2)	182 (37.4)	--***
Unit Weight of Wall on a Volume Basis,* kg/m^3 (lb/ft^3)	898 (56.0)	--***
Average Wall Thickness, mm (in.)	203 (8.00)	207 (8.13)
Wall Area, m^2 (ft^2,)	6.86 (73.88)	6.87 (73.92)
Estimated Moisture Content**, % ovendry weight	2	2

*Before calibrated hot box tests.
**Estimated from air dry and ovendry weights of thermal conductivity specimens.
***Not calculated because Wall S is not homogeneous.

Table 3 - Summary of Physical Properties for Walls L and S

Wall Designation	Wall Mean Temp.,* °C (°F)	tc Climatic Chamber Temp., °C (°F)	tm Metering Chamber Temp., °C (°F)	Δt Surface-to-Surface Temp. Diff., °C (°F)	q** Heat Flow, W/sq m (Btu/hr•sq ft)	Rt*** Thermal Resistance, sq m•K/W (hr•sq ft•°F/Btu)	k Thermal Conductivity, W/m•K (Btu•in./hr•sq ft•°F)
L	2.7 (36.9)	-17.3 (0.9)	21.3 (70.4)	32.3 (58.2)	38.5 (12.2)	0.99 (5.6)	0.24 (1.68)
L	13.2 (55.7)	3.7 (38.6)	21.9 (71.4)	15.1 (27.1)	17.2 (5.5)	1.02 (5.8)	0.23 (1.61)
L	29.8 (85.6)	36.2 (97.2)	22.7 (72.8)	12.3 (22.2)	17.4 (5.5)	0.86 (4.9)	0.29 (1.99)
L	39.8 (103.7)	55.8 (132.5)	23.2 (73.7)	28.7 (51.6)	40.2 (12.7)	0.86 (4.9)	0.28 (1.97)
S	3.3 (37.9)	-15.9 (3.3)	21.5 (70.7)	31.3 (56.3)	44.9 (14.2)	0.85 (4.8)	-
S	13.7 (56.7)	4.6 (40.3)	22.0 (71.6)	14.4 (25.9)	21.6 (6.9)	0.81 (4.6)	-
S	30.6 (87.0)	37.5 (99.5)	23.0 (73.4)	12.4 (22.4)	18.1 (5.7)	0.85 (4.8)	-
S	40.6 (105.1)	56.8 (134.3)	23.7 (74.7)	28.3 (51.0)	43.8 (13.9)	0.79 (4.5)	-

* Average of metering and climatic wall surface temperatures.
** Heat flow through wall measured by calibrated hot box (ASTM Designation: C976).
*** Overall thermal resistance calculated using design surface coefficients of 0.15 sq m• K/W (0.85 hr•sq ft•°F/Btu) and measured values of heat flow.

Table 4 - Steady-State Results From Calibrated Hot Box Tests

Specimen		Overall Dimensions, mm (in.)	Average Thickness, mm (in.)	Ovendry Unit Weight, kg/cu m (pcf)
Wall L Lightweight Concrete	Top	310 x 306 (12.2 x 12.1)	50 (1.98)	771 (48.1)
	Bottom	306 x 307 (12.1 x 12.1)	52 (2.03)	750 (46.8)
Wall S Lightweight Concrete	Top	305 x 305 (12.0 x 12.0)	51 (1.99)	805 (50.2)
	Bottom	305 x 305 (12.0 x 12.0)	50 (1.99)	801 (50.0)
Wall S Normal Weight Concrete	Top	305 x 305 (12.0 x 12.0)	51 (2.00)	2260 (141)
	Bottom	305 x 305 (12.0 x 12.0)	51 (2.02)	2270 (142)

Table 5 - Measured Properties of Guarded Hot Plate Test Specimens

Layer	R Thermal Resistance, sq m•K/W (hr•sq ft•°F/Btu)		
	Wall L	Wall S Ltwt Concrete	Wall S NW Concrete
Outside Air Film	0.03 (0.17)	0.03 (0.17)	0.03 (0.17)
200 mm Thick Concrete Wall (8-in.)	0.98* (5.59)	0.97* (5.49)	0.11* (0.64)
Inside Air Film	0.12 (0.68)	0.12 (0.68)	0.12 (0.68)
Total R	1.13 (6.44)	1.12 (6.34)	0.26 (1.49)

* Calculated from guarded hot plate thermal conductivities of ovendry specimens at 24°C (75°F) and measured wall thickness.

Wall S R-value calculated using ASHRAE parallel path method (Ref. 10):

U=(1/1.49)•(6/103)+(1/6.34)•(97/103)
=0.188 Btu/hr•sq ft•°F
=1.07 W/sq m•K

R=1/U = 5.33 hr•sq ft•°F/Btu
=0.94 sq m•K/W

Table 6 - Predicted Thermal Resistance of Walls L and S

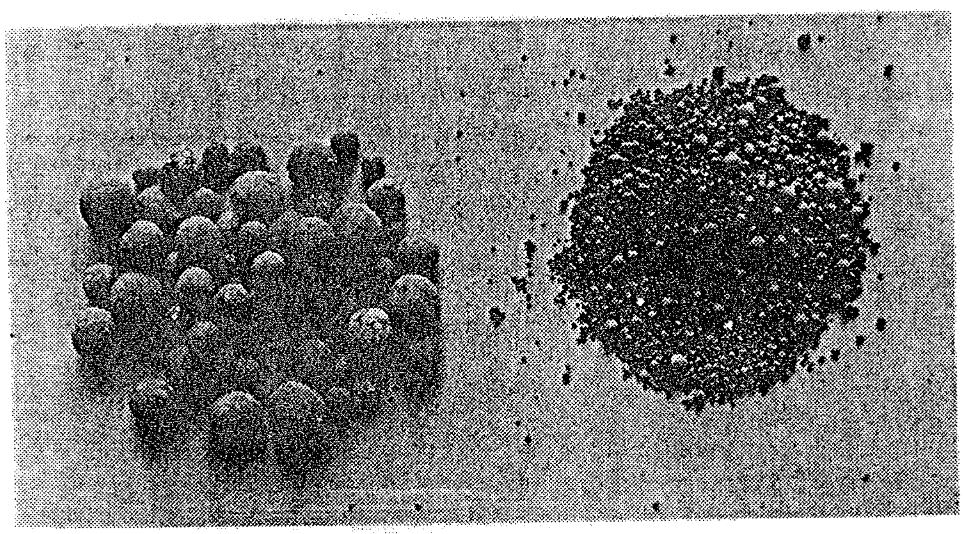

Figure 1

3M Macrolite Ceramic Spheres

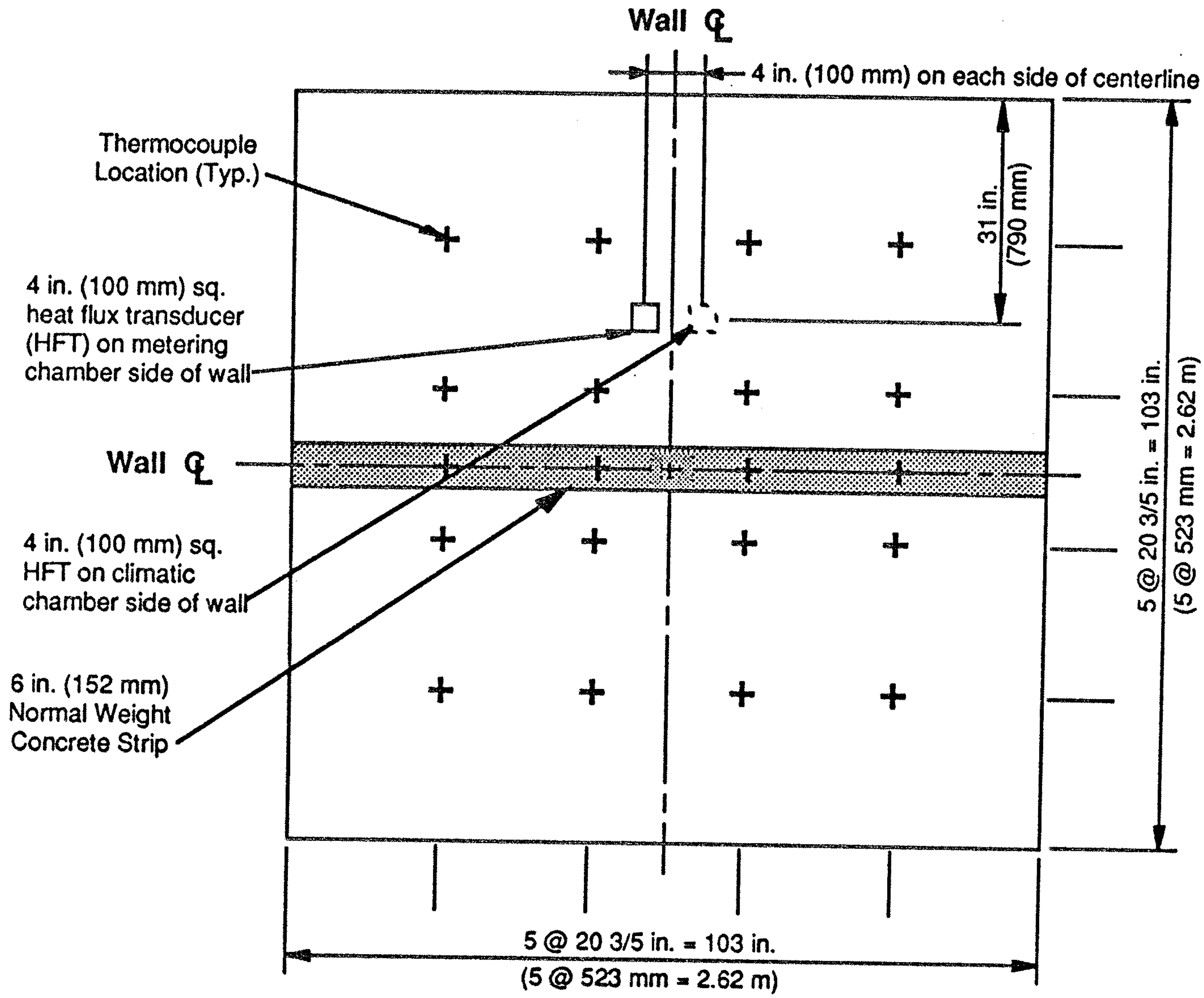

Figure 2

Wall S Air, Surface, and Internal Thermocouple Locations

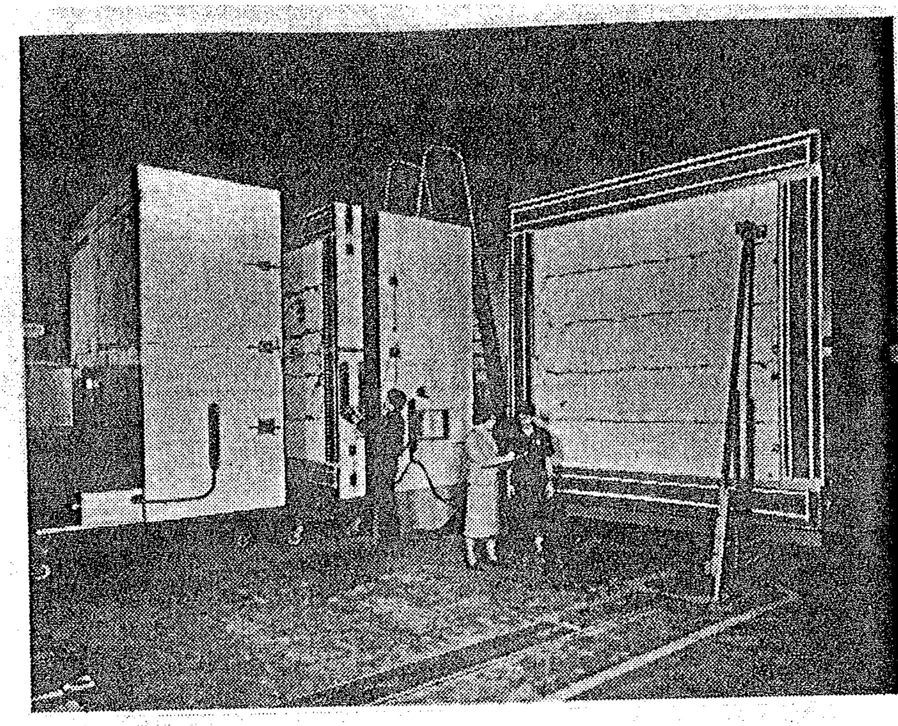

Figure 3 Calibrated Hot Box Test Facility

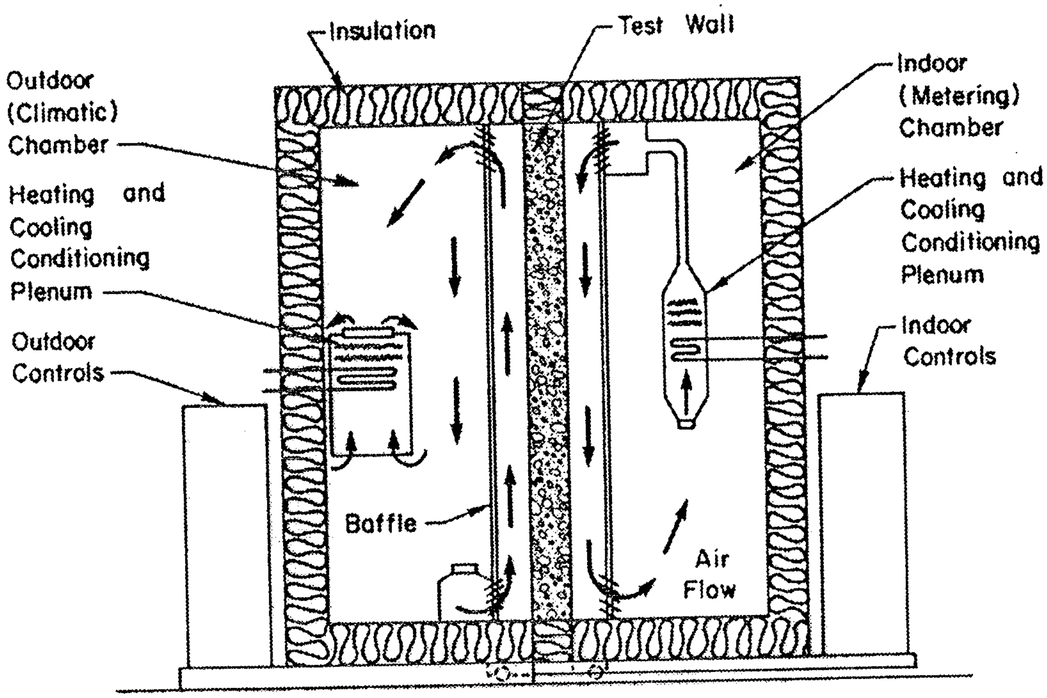

Figure 4 Schematic of Calibrated Hot Box

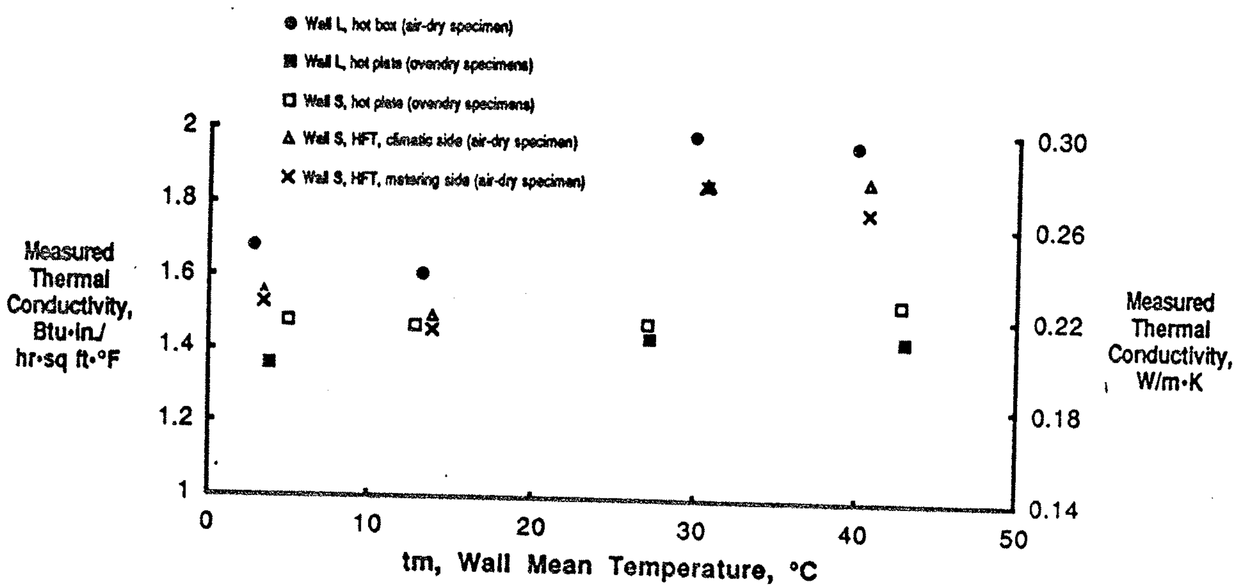

Figure 5

Measured Thermal Conductivity of Lightweight Concrete

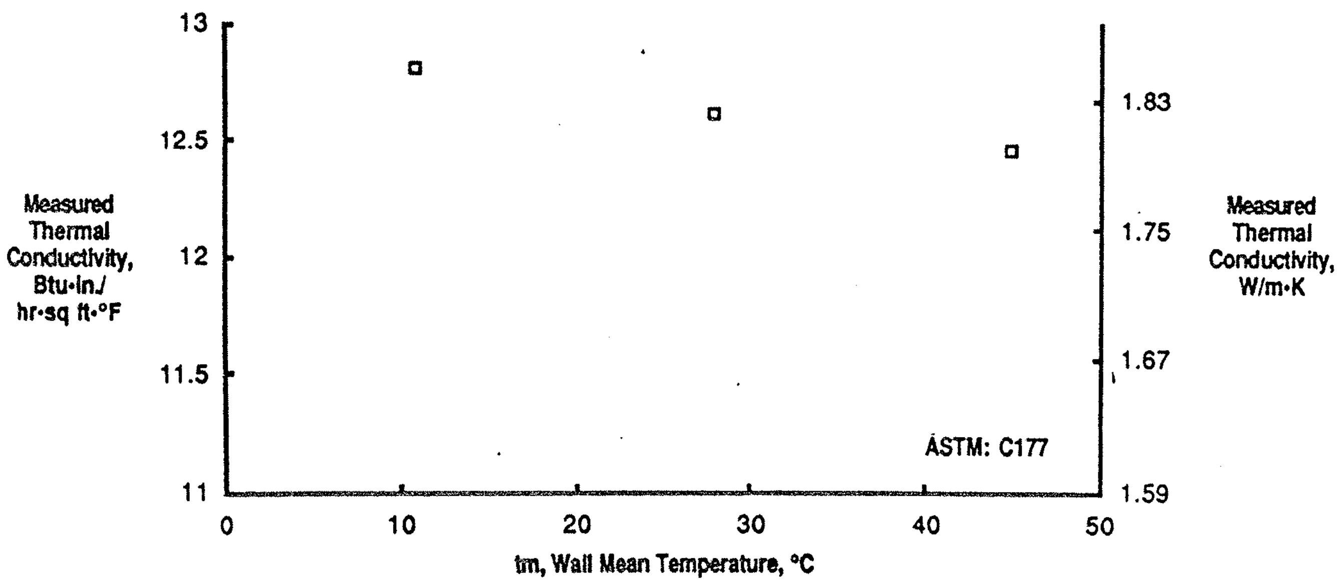

Figure 6

Measured Thermal Conductivity of Normal Weight Concrete