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Martha G. Van Geem[1]

Heat Transfer Characteristics of a Recently Developed Lightweight Structural Concrete

REFERENCE: Van Geem, M. G., **"Heat Transfer Characteristics of a Recently Developed Lightweight Structural Concrete,"** *Insulation Materials, Testing, and Applications, ASTM STP 1030,* D. L. McElroy and J. F. Kimpflen, Eds., American Society for Testing and Materials, Philadelphia, 1990, pp. 437-463.

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/m³ (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./h · ft² · °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/m³ (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./h · ft² · °F).

The portland cement concrete developed for this project can be used to combine structural, thermal insulation, and heat storage capacity functions of exterior walls in one element. For many climates this concrete can be used without additional insulation as a complete wall system in low-rise buildings.

Heat transfer characteristics of two 200-mm (8-in.)-thick, full-size wall assemblies were evaluated using a calibrated hot box (ASTM C 976). 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 midheight. The horizontal strip simulates a floor slab extending through an exterior wall.

Overall thermal resistances of Walls L and S, respectively, are 0.92 and 0.83 m² · K/W (5.2 and 4.7 h · ft² · °F/Btu) at 24°C (75°F). Thermal resistance of Wall S is 11% less than that for Wall L.

Tests under dynamic temperature conditions provide a measure of thermal response for selected temperature ranges. Dynamic response includes heat storage capacity as well as heat transmission characteristics of the wall assembly. Results from a 24-h period, sol-air temperature cycle showed that heat storage capacity of the low density concrete delayed heat flow through the test specimen. Average thermal lag for the 200-mm (8-in.)-thick lightweight concrete wall was 6 h.

Thermal and physical properties of the lightweight concrete were also measured on small-scale specimens. Concrete thermal conductivity, thermal diffusivity, specific heat, compressive strength, flexural strength, splitting tensile strength, shear strength, modulus of elasticity, drying shrinkage, and freeze/thaw resistance were determined.

Laboratory test results provide information on the thermal and physical performance of the new lightweight concrete.

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

This paper summarizes results from a project to develop portland cement concrete with sufficient thermal resistance and strength properties to serve as an effective thermal break in building envelopes.

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A thermal break is an exterior building element made of a material with a high thermal resistance used in place of a material with a lower thermal resistance to reduce energy losses through a building envelope. A thermal break may range in size from a small plastic nail used in place of a metal nail, to a large sheet of insulation used to prevent energy losses through a building foundation. The term "structural" used as an adjective to "thermal break" implies that the material has load bearing capabilities.

A concrete was developed with an air-dry unit weight of 800 kg/m^3 (50 pcf), a compressive strength of approximately 13.8 MPa (2000 psi), and a thermal conductivity of 0.23 W/m · K (1.6 Btu · in./h · ft^2 · °F). Although it is envisioned that concrete with these properties could be used for many building components, project emphasis is 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 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.

Objectives and Scope

Project work is reported in Refs *1* to *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.

Heat flow through two walls was measured in the calibrated hot box test facility (ASTM C 976) at Construction Technology Laboratories, Inc. (CTL). One test specimen, designated Wall L, was an 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 midheight. The horizontal strip simulates a floor slab extending through an exterior wall.

Walls were tested for steady-state temperature conditions to obtain average heat transmission coefficients, including total thermal resistance (R_T) and thermal transmittance (U). A comparison of test results for the two walls shows the effect of the normal weight concrete strip.

Wall L, the homogeneous concrete wall, was also tested under dynamic temperature conditions. Dynamic tests provided a measure of thermal response for selected temperature ranges. A simulated sol-air dynamic cycle was selected to permit comparison of results with those obtained in previous investigations [*4-6*].

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).

Background

Concrete developed for this program will have lower heat transmission than concrete commonly used for low-rise building construction. A wall with low heat transmission will conserve energy.

Types of Concrete

Concrete is available in a wide range of weights and strengths. Normal weight concrete utilizes sand and gravel aggregate and is most commonly used for construction of structural concrete members. Normal weight concretes have a unit weight of approximately 2320 kg/m^3 (145 pcf), and compressive strengths of approximately 17 to 41 MPa (2500 to 6000 psi) are common. High-strength normal weight concretes have been developed with strengths exceeding 100 MPa (15 000 psi). Measured thermal conductivities of normal weight concretes range from 1.4 to 2.9 W/m · K (10 to 20 Btu · in./h · ft^2 · °F).

Concretes in the 1440 to 2080 kg/m^3 (90 to 130 pcf) range are known as structural lightweight concretes. These concretes have compressive strengths in the range of 17.2 to over 62.1 MPa (2500 to over 9000 psi), depending on materials, mix design, and other factors. Lightweight concretes typically have thermal conductivities ranging from 0.6 to 1.9 W/m · K (4 to 13 Btu · in./h · ft^2 · °F).

While normal weight and structural lightweight concretes have more than adequate strength for the proposed use, their thermal properties may be inadequate for external walls.

Concretes weighing 800 kg/m^3 (50 pcf) or less are called *insulating concretes.* Current technology limits the compressive strengths of these concretes to about 4.1 MPa (600 psi) [*7*]. These concretes typically have thermal conductivities of 0.07 to 0.22 W/m · K (0.5 to 1.5 Btu · in./h · ft^2 · °F).

A second category of lightweight concretes is in the weight range of 800 to about 1440 kg/m^3 (50 to about 90 pcf). These are usually called *fill concretes.* Concretes in this weight range have not been widely used and their development has been somewhat neglected. This is because of generally poor strength-weight relationships available with these concretes. However, it is at the lower limit of this category, in the range of 720 to 800 kg/m^3 (45 to 55 pcf) concrete, that an effort has been made to develop concrete which will meet strength and thermal resistance requirements desirable for external walls in low-rise buildings. Concretes with unit weights of 720 to 800 kg/m^3 (45 to 55 pcf) have thermal conductivities of approximately 0.22 W/m · K (1.5 Btu · in./h · ft^2 · °F).

Thermal Properties of Concrete

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./h · 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./h · ft^2 · °F).

Heat flow through a homogeneous wall subjected to steady-state temperature conditions is linearly related to the thermal conductivity of the wall material and the temperature differential across the wall. For dynamic temperature conditions, heat flow is dependent on the storage capacity of the wall material in addition to its thermal conductivity.

Exterior building walls are seldom in a steady-state condition. Outdoor air temperatures and solar effects cause cyclic changes in outdoor surface temperatures.

A conditioned building with high mass walls will have less energy losses to the outdoor environment than an identical building with low mass walls of equivalent thermal resistance [*1*]. Energy savings are most significant for outdoor diurnal temperature cycles that cause reversals in heat flow through walls.

Optimally, the least heat will flow through a wall having high thermal resistance and high storage capacity. Heat transmission properties are more sensitive to changes in thermal resistance than to changes in storage capacity. The goal of this project is to develop a concrete with the highest thermal resistance and therefore the lowest unit weight. The concrete unit weight is limited by the need for sufficient structural capacity, because strength generally decreases with decreasing unit weight.

Concrete Mix Development

Portland Cement Concrete

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 reduced is limited.

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 had to be 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.[2]

Structural lightweight aggregates are available in all parts of the country. Many of these aggregates are capable of producing relatively high strength concrete in the weight range of 1400 to 1800 kg/m^3 (90 to 115 pcf).

The aggregates used in this investigation were limited to those known by the principal investigator, by previous experience, to be capable of producing lower weight concretes with adequate strength, or those found in a search for additional desirable aggregates. Acceptance of an aggregate or concrete mix design was based on compressive strength and unit weight. Other properties were not determined on those mixes that did not meet the strength-to-weight criteria.

Preliminary Mix Development

Concrete mixes were made using seven aggregates, singly or in combination (Table 1). The number of mixes made with each aggregate varied from one to twelve, depending on the aggregate's potential for meeting the weight and strength objectives. Aggregate combinations were used in many cases in an attempt to take advantage of desirable properties found in fine or coarse sizes of certain aggregates.

The last column in Table 1 shows the average strength-to-weight ratio for mixes made with different aggregate combinations. Mixes utilizing 3M Macrolite[3] 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 (Fig. 1) is a recently developed ceramic supplied by the 3M Company of St. Paul, Minnesota. According to the company, arrangements are being made to produce this material commercially. A unique feature of this aggregate is that it has a relatively low water absorption of less than 0.5%. Most 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 300 μm (No. 4 to No. 50).[4]

Fillite, furnished by Fillite USA, Inc. of Huntington, West Virginia, 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 300 μm. Fillite was used to provide a very fine lightweight material to those aggregates which were deficient in that size range.

Tufflite is a naturally occurring volcanic pumice aggregate. Livlite is an expanded clay aggregate. Liapor and Leca are expanded shale aggregates produced by grinding and pelletizing shales or clays and firing in a rotary kiln. Thus Liapor and Leca are spherical compared to Tufflite and Livlite which are irregularly shaped.

Most aggregates had relatively high water absorptions and were batched in a saturated condition to avoid rapid stiffening during mixing. However, the 3M Macrolite had an extremely low absorption and was batched in a dry condition.

[2]The strength-to-weight ratio is the ratio of the concrete's compressive strength to its unit weight.
[3]Product names used in this paper may be trademarked.
[4]Aggregate sizes are described by sieve opening sizes in accordance with ASTM Specification for Wire-Cloth Sieves for Testing Purposes (E 11).

TABLE 1—*Portland cement concrete unit weights and compressive strengths.*

Aggregate(1)	No. of Mixes	Unit Weight, kg/m^3 (pcf)		Compressive Strength,(4) MPa (psi)		Strength-to-Weight Ratio(6) kPa/(kg/m^3), (psi/pcf)
		Fresh(2)	28 day(3)	7 day(5)	28 day(3)	
Project Objective	—	—	800 (50)	—	10.3 (1500)	12.9 (30.0)
Tufflite	1	1299 (81.2)	898 (56.1)	3.4 (490)	5.9 (850)	6.6 (15.2)
Tufflite & Fillite	1	1278 (79.9)	941 (58.8)	4.2 (610)	7.0 (1020)	7.4 (17.3)
Liapor	3	1005 (62.8)	898 (56.1)	5.4 (780)	8.0 (1160)	8.9 (20.7)
Liapor & Fillite	4	1064 (66.5)	962 (60.1)	8.2 (1190)	11.0 (1600)	11.4 (26.6)
Liapor, Fillite & PQ Microspheres	1	1010 (63.1)	896 (56.0)	8.5 (1230)	9.5 (1380)	10.6 (24.6)
Liapor, Fillite & 3 M Macrolite	2	896 (56.0)	829 (51.8)	10.7 (1550)	11.6 (1680)	14.0 (32.4)
Tufflite & Liapor	1	1107 (69.2)	1014 (63.4)	9.0 (1300)	11.0 (1590)	10.8 (25.1)
Livlite & Liapor	1	1117 (69.8)	997 (62.3)	8.1 (1170)	10.2 (1480)	10.2 (23.8)
Livlite	1	1275 (79.7)	1080 (67.5)	7.9 (1150)	15.0 (2170)	13.9 (32.1)
Livlite & Fillite	1	1213 (75.8)	970 (60.6)	4.0 (580)	10.3 (1500)	10.6 (24.8)
Leca	1	1062 (66.4)	941 (58.8)	4.1 (600)	6.8 (980)	7.2 (16.7)
3M Macrolite & Fillite	8	790 (49.4)	779 (48.7)	9.6 (1400)	12.3 (1780)	15.8 (36.6)

(1) Product names used in this paper may be trademarked.
(2) ASTM Designation: C 138, "Standard Test Method for Unit Weight, Yield, and Air Content (Gravimetric) of Concrete"
(3) Measured on 100x200-mm (4x8-in.) and 150x300-mm (6x12-in.) cylinders moist-cured 7 days at 23±1.7°C (73.4±3°F) and 100% RH, and then air-dried at 23±1.7°C (73.4±3°F) and 50±5% RH for the remaining 21 days.
(4) ASTM Designation: C 39, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens"
(5) Measured on 100x200-mm (4x8-in.) and 150x300-mm (6x12-in.) cylinders moist-cured at 23±1.7°C (73.4±3°F) and 100% RH for 7 days.
(6) Ratio of 28-day compressive strength to 28-day air-dry unit weight.

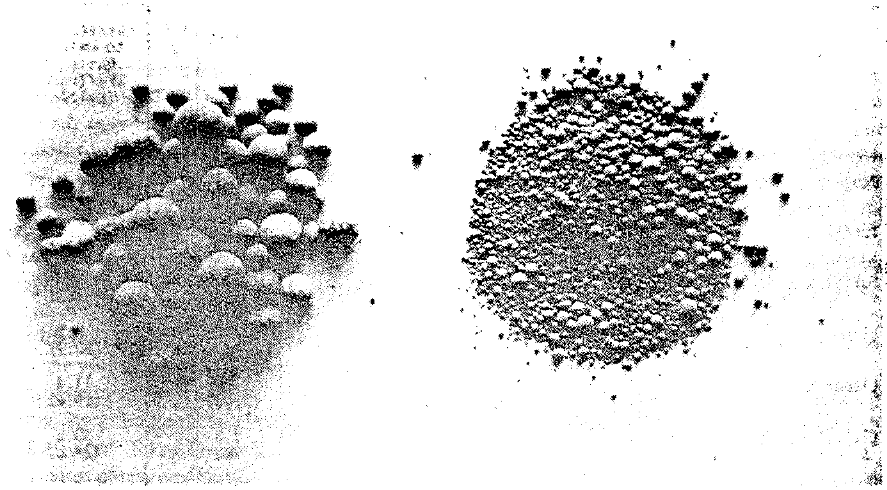

FIG. 1—*3M Macrolite Ceramic Spheres.*

Final Mix Design

The final mix design is shown in Table 2. 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 unit weight of about 800 kg/m³ (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 are similar to those presented in Table 2. Test results are summarized in Table 3. 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 2.62 by 2.62 m (103 by 103 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 midheight. Average thickness of Wall S is 206 mm (8.13 in.).

TABLE 2—*Final portland cement concrete mix design.*

Material	Quantities per 1.0 m³ (Quantities per 1.0 cu yd)		
	Absolute Volume, m³ (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%.

The concrete mix for Walls L and S are presented in Table 2. 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 midthickness.

Threaded concrete inserts were cast into the walls at midthickness to aid in transporting walls after concrete had attained the necessary strength.

Walls L and S were allowed to cure in the formwork for approximately two 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 three months. Wall S was air dried in the laboratory at a temperature of 21 ± 6°C (70 ± 10°F) for approximately four months.

Before 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 4. Wall weights immediately before and after calibrated hot box tests are presented.

Reference *3* more fully describes wall construction.

TABLE 3—*Physical and thermal properties of hardened concrete.*

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. 8)	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. 8)	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.

Instrumentation

Eighty 20-gage, Type T thermocouples, corresponding to ASTM Temperature-Electromotive Force (EMF) Tables for Standardized Thermocouples (E 230), 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 midthickness. The 16 thermocouples in each plane were spaced 525 mm (20³/s in.) apart in a 4 × 4 grid over the wall area (Figs. 2 and 3).

An additional four thermocouples were located on each wall surface and at concrete midthickness along the centerline of the normal weight concrete strip of Wall S (Fig. 3).

TABLE 4—*Summary of physical properties for Walls L and S.*

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,* kg/m² (lb/ft²)	182 (37.4)	--***
Unit Weight of Wall,* kg/m³ (lb/ft³)	898 (56.0)	--***
Average Wall Thickness, mm (in.)	203 (8.00)	207 (8.13)
Wall Area, m² (ft².)	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.

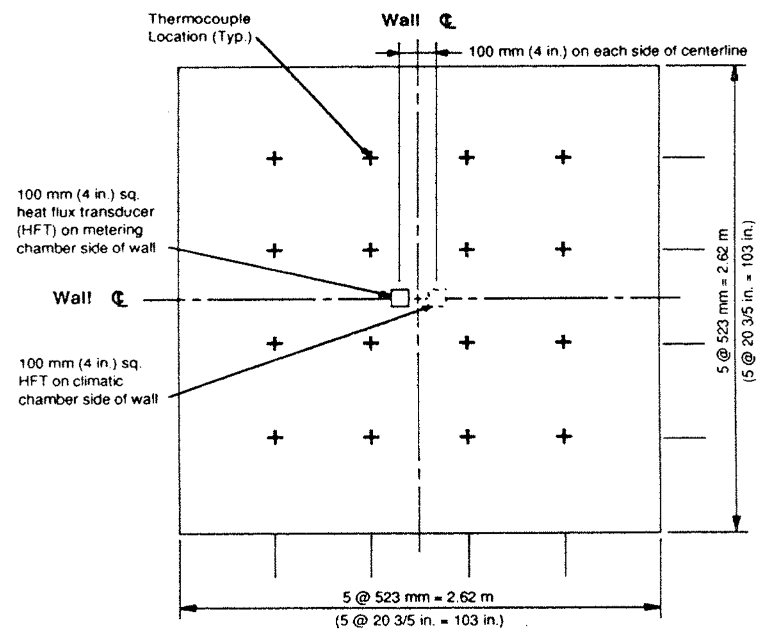

FIG. 2—*Wall L air, surface, and internal thermocouple locations.*

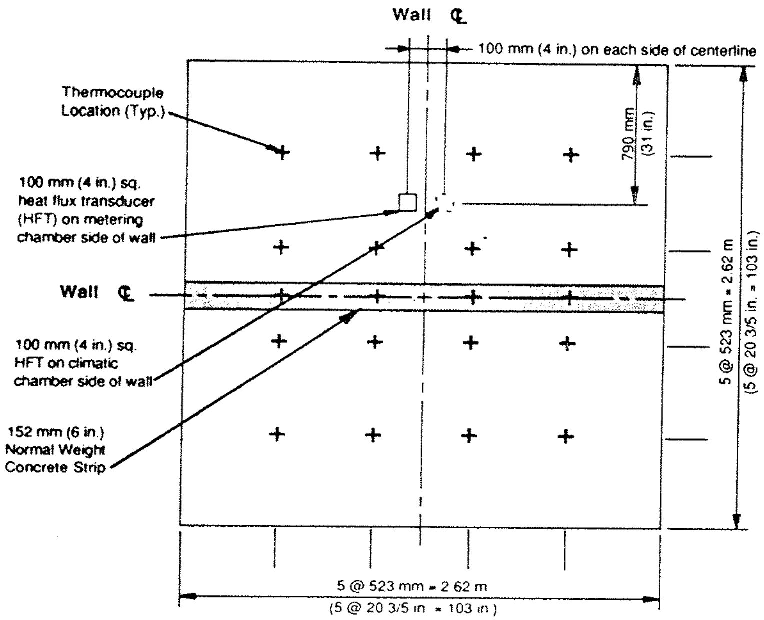

FIG. 3—*Wall S air, surface, and internal thermocouple locations.*

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 midthickness 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. Thermocouples were wired to form a thermopile such that an electrical average of four thermocouple junctions, located along a horizontal line across the grid, was obtained. Wires for internal thermocouples were routed through side formwork before casting the second 100-mm (4-in.) concrete layer.

One heat flux transducer measuring 100 by 100 mm (4 by 4 in.) was mounted on each of the indoor and outdoor surfaces of the test walls. Sensors were located near the center of the walls (Figs. 2 and 3). The surface of the heat flux transducer in contact with a wall surface was coated with a thin layer of high-conductivity silicon grease. The silicon grease provided uniform contact between the heat flux transducer and wall surface. Duct tape was used to secure heat flux transducers to the wall surfaces. The duct tape was painted the same color as the test wall surface. Heat flux transducers were calibrated using results from steady-state calibrated hot box tests on Wall L.

Calibrated Hot Box Test Facility

Heat flow through Walls L and S was measured under steady-state and dynamic temperature conditions. Tests were conducted in the calibrated hot box facility shown in Figs. 4 and 5. Tests

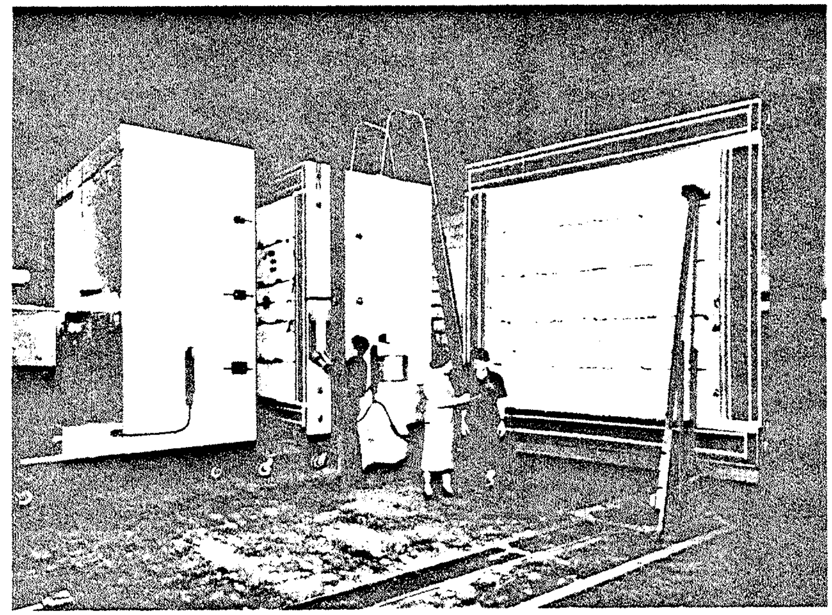

FIG. 4—*Calibrated hot box test facility.*

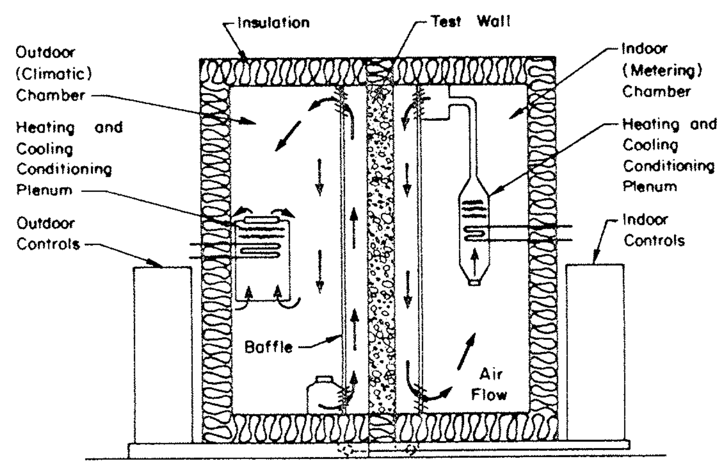

FIG. 5—*Schematic of calibrated hot box.*

were performed in accordance with ASTM Test for Thermal Performance of Building Assemblies by Means of a Calibrated Hot Box (C 976).

The following paragraphs give a brief description of the calibrated hot box. Instrumentation and calibration details are described in Refs *3* and *9*.

The facility consists of two highly insulated chambers (Fig. 5). The walls, ceiling, and floors of each chamber are insulated with foamed urethane sheets to obtain a nominal thickness of 300 mm (12 in.). During tests, the chambers are clamped tightly against an insulating frame that surrounds the test wall. Air in each chamber is conditioned by heating and cooling equipment to obtain desired temperatures on each side of the test wall.

The climatic (outdoor) chamber can be held at a constant temperature or cycled within the range of −26 to 54°C (−15 to 130°F). Temperatures can be programmed for a 24-h cycle to obtain the desired temperature-time relationship. The metering (indoor) chamber, which simulates an indoor environment, can be maintained at a constant room temperature between 18 and 27°C (65 and 80°F).

The specimen is oriented vertically in the CTL calibrated hot box. Therefore heat flows horizontally through the wall. The facility was designed to accommodate walls with thermal resistance values ranging from 0.26 to 3.52 $m^2 \cdot K/W$ (1.5 to 20 $h \cdot ft^2 \cdot °F/Btu$).

The pressure in both the metering and climatic chambers is atmospheric.

Thermal Properties of Concrete for Steady-State Temperature Conditions

Thermal resistances of Walls L and S were measured using the 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

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).

Test Procedures—Steady-state calibrated hot box tests were conducted by maintaining constant indoor and outdoor chamber temperatures. Results are calculated from data collected when specimen temperatures reach equilibrium and the rate of heat flow through the test wall is constant.

Hot box tests on Wall L were performed in April 1986. Tests on Wall S were performed in July and August 1986.

Test Results—Steady-state results from calibrated hot box tests on Walls L and S are summarized in Table 5. 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 5 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 5 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 standard surface resistance coefficients of 0.03 $m^2 \cdot K/W$ (0.17 $h \cdot ft^2 \cdot °F/Btu$) for outdoor air and 0.12 $m^2 \cdot K/W$ (0.68 $h \cdot ft^2 \cdot °F/Btu$) for indoor air *[10]*.

Measured relative humidity within the metering and climatic chambers of the CTL calibrated hot box is also listed in Table 5. Metering chamber relative humidity is greater for Wall S tests

TABLE 5—*Steady-state results from calibrated hot box tests.*

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)	Relative Humidity		Laboratory Air Temperature	
								Metering Chamber, %	Climatic Chamber, %	Max., (°C) °F	Min., (°C) °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)	35	20	24 (75)	23 (74)
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)	34	17	24 (75)	22 (72)
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)	33	11	23 (74)	22 (72)
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)	33	10	24 (75)	23 (73)
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)	-	55	21	23 (74)	23 (74)
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)	-	53	18	23 (74)	23 (74)
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)	-	51	12	26 (79)	24 (75)
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)	-	51	10	27 (80)	26 (78)

* 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.

than for Wall L tests because of a higher laboratory relative humidity when Wall S tests were started.

Maximum and minimum laboratory air temperatures obtained during each steady-state test are also listed in Table 5. The laboratory acts as a guard for the metering chamber during tests conducted in CTL's calibrated hot box.

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 · in./h · ft² · °F) at 24°C (75°F). Overall thermal resistances of Walls L and S, respectively, are 0.92 and 0.83 m² · K/W (5.2 and 4.7 h · ft² · °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 Test for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus (C 177) and ASTM Practice for the Calculation of Thermal Transmission Properties from Steady-State Heat Flux Measurements (C 1045).

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 50 by 300 by 300 mm (2 by 12 by 12 in.). Specimens were moist-cured at 23 ± 1.7°C (73.4 ± 3°F) and 100% RH for seven days, then air-dried at 23 ± 3°F (73 ± 5°F) and 45 ± 15% RH. Specimens were ovendried before testing to eliminate effects of moisture migration during testing. Measured specimen dimensions and unit weights are given in Table 6.

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.

TABLE 6—*Measured properties of guarded hot plate test specimens.*

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)

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 Ref *11*.

Test Results—Guarded hot plate test results are presented in Fig. 6 for Walls L and S lightweight concrete specimens and Fig. 7 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.

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./h · ft² · °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 one ninth that for normal weight concrete.

Heat Flux Transducer Test Results

Test Procedures—Two heat flux transducers (HFTs) were mounted on each wall specimen as shown in Figs. 2 and 3 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 HFTs for Wall S. Heat flow through Wall S as measured by the HFT's was determined in accordance with ASTM Practice for In-Situ Measurement of Heat Flux and Temperature on Building Envelope Components (C 1046).

Test Results—Heat flux transducer test results for the lightweight concrete portion of Wall S are presented in Fig. 6. 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./h · ft² · °F).

Discussion of Results

Figure 6 presents thermal conductivities of the lightweight concrete measured by the calibrated hot box (ASTM C 976), the guarded hot plate (ASTM C 177), and heat flux transducers (ASTM C 1046). 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. An increase in specimen moisture content increases thermal conductivity.

Predicted thermal resistances of Walls L and S are presented in Table 7. Values are calculated using results from guarded hot plate tests on ovendry specimens and measured wall thicknesses. Calculation procedures are from the *ASHRAE Handbook - 1985 Fundamentals* [*10*].

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 oven-dried specimens and measured values are based on air-dried specimens.

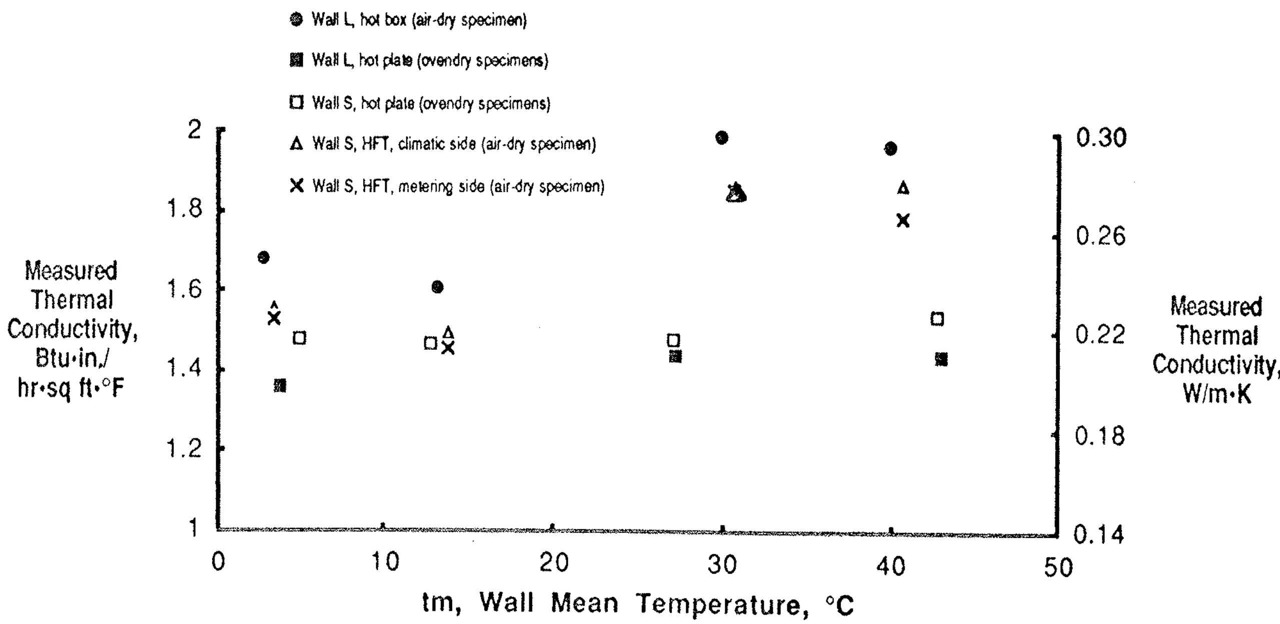

FIG. 6—*Measured thermal conductivity of lightweight concrete.*

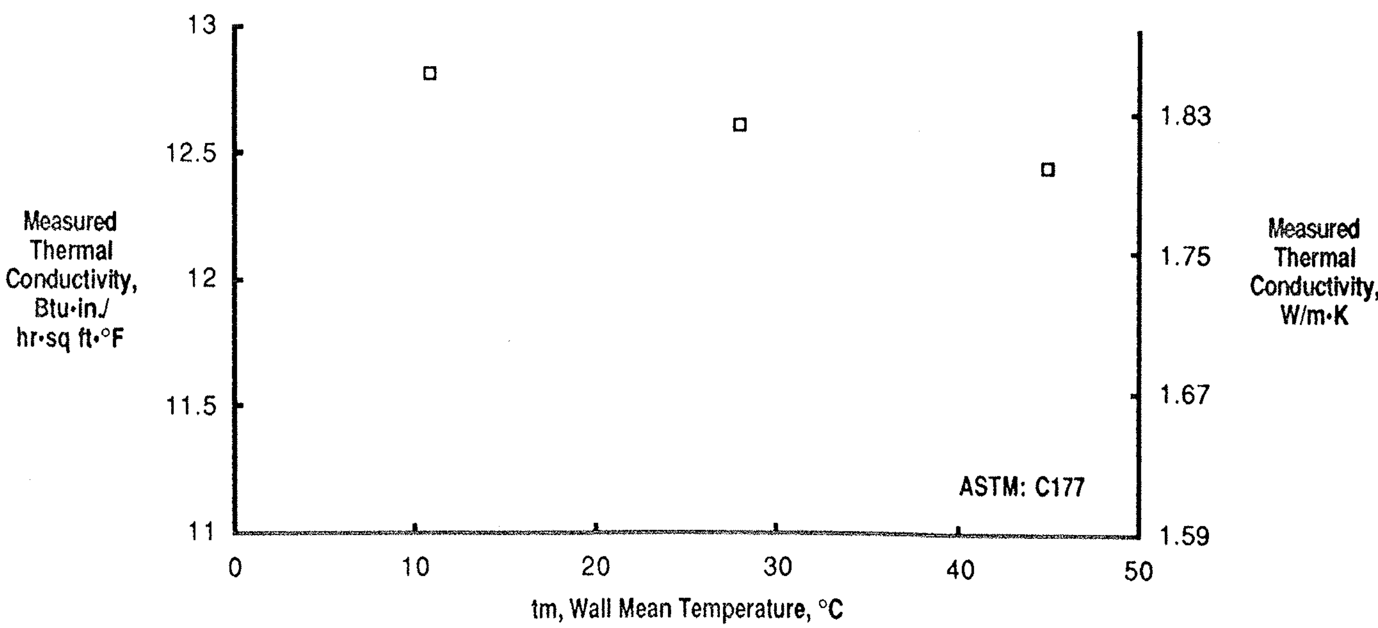

FIG. 7—*Measured thermal conductivity of normal weight concrete.*

TABLE 7—*Predicted thermal resistance of Walls L and S.*

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

Dynamic Calibrated Hot Box Tests

Exterior building walls are seldom subjected to steady-state thermal conditions. Outdoor air temperatures and solar effects cause cyclic changes in outdoor surface temperatures. Generally, indoor surface temperatures are relatively constant compared to outdoor surface temperatures.

Dynamic tests are a means of evaluating thermal response under controlled conditions that simulate temperature changes actually encountered in building envelopes. Heat flow through walls as a response to temperature changes is a function of both thermal resistance and thermal storage capacity.

Test Procedures

The lightweight concrete wall, designated Wall L, was subjected to four dynamic temperature cycles using the CTL calibrated hot box. For these tests, the calibrated hot box metering chamber air temperatures were held constant, while climatic chamber air temperatures were cycled over a pre-determined time versus temperature relationship. The rate of heat flow through a test specimen was determined from hourly averages of data.

Results for one cycle, denoted the NBS Temperature Cycle, are presented. Results for other test cycles are presented in Ref *3*. The NBS Test Cycle has been applied to more than 25 walls in previous CTL calibrated hot box studies [*12,13*]. This periodic cycle is based on a simulated sol-air[5] cycle used by the National Bureau of Standards in their evaluation of dynamic thermal performance of an experimental masonry building [*14*]. It represents a large variation in outdoor temperature over a 24-h period. The mean climatic chamber temperature of the cycle is approximately equal to the mean metering chamber temperature.

[5]Sol-air temperature is that temperature of outdoor air that, in the absence of all radiation exchanges, would give the same rate of heat entry into the surface as would exist with the actual combination of incident solar radiation, radiant energy exchange, and convective heat exchange with outdoor air [*10*].

A dynamic cycle is repeated until a condition of equilibrium is obtained. Equilibrium conditions were evaluated by consistency of applied temperatures and measured energy response. After an equilibrium condition was reached, the test was continued for a period of three days. Results are based on average readings for three consecutive 24-h cycles.

Test Results

Measured temperatures for the NBS Temperature Cycle applied to Wall L are presented in Fig. 8. Climatic chamber air (t_c), metering chamber air (t_m), climatic surface (t_{cs}), metering surface (t_m), and internal wall (t_{md}) temperatures are average readings of 16 thermocouples placed as described in the Instrumentation section. The average climatic chamber air temperature was 20.2°C (68.3°F). The average metering chamber air temperature was 22.3°C (72.1°F).

Measured heat flow for the NBS Temperature Cycle applied to Wall L is presented in Fig. 9. Heat flow is designated positive when heat flows from the calibrated hot box climatic chamber to the metering chamber. Heat flow determined from calibrated hot box tests (ASTM C 976) is denoted q_w.

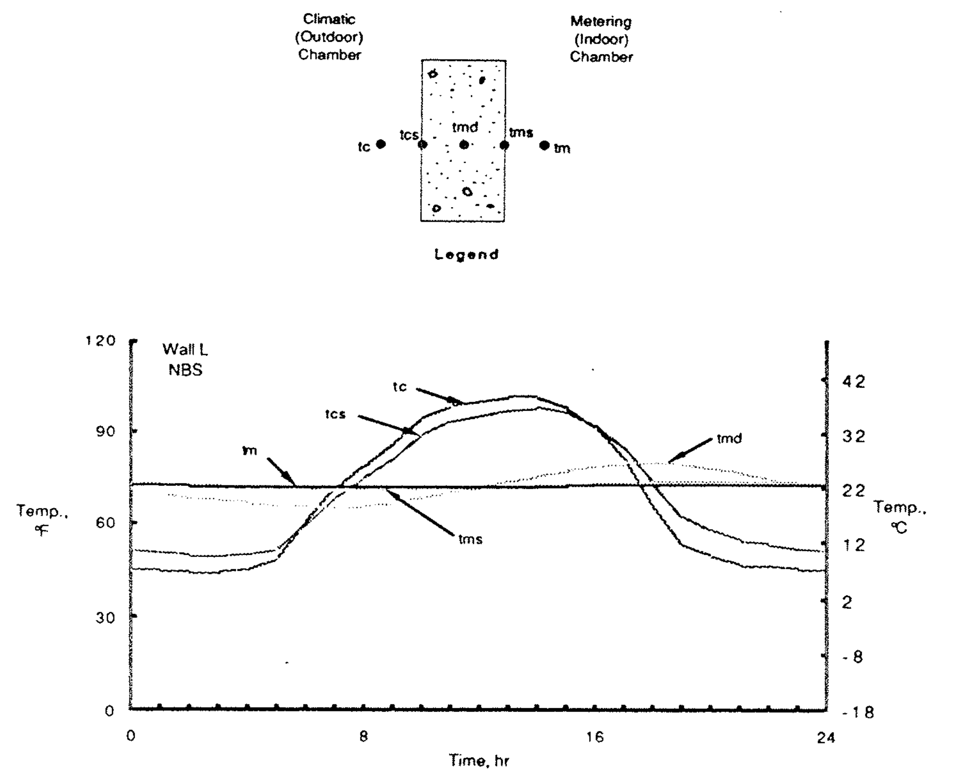

FIG. 8—*Measured temperatures for NBS test cycle applied to Wall L.*

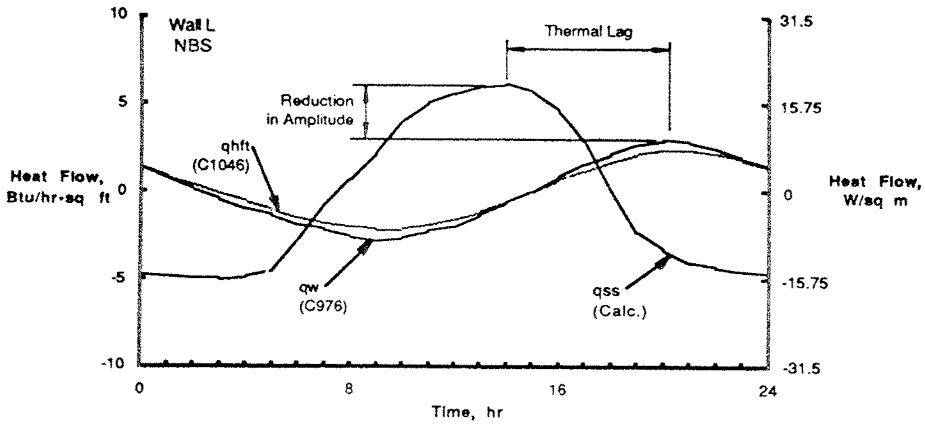

FIG. 9—*Measured heat flow for NBS test cycle applied to Wall L.*

Heat flow from the heat flux transducer (ASTM C 1046) located on the metering chamber side of the test specimen surface is denoted q_{hft}. Heat flux transducer data were calibrated using results from steady-state calibrated hot box tests on Wall L.

Heat flow predicted by steady-state analysis is denoted q_{ss}. Values were calculated on an hourly basis from wall surface temperatures using the equation

$$q_{ss} = (t_{ms} - t_{cs})/R \tag{1}$$

where

q_{ss} = heat flow through wall predicted by steady-state analysis, W/m² (Btu/h · ft²),
R = average thermal resistance, m² · K/W (h · ft² · °F/Btu),
t_{cs} = average temperature of wall surface, climatic chamber side, °C (°F), and
t_{ms} = average temperature of wall surface, metering chamber side, °C (°F).

Thermal resistances are dependent on wall mean temperature and were derived from steady-state calibrated hot box test results.

Measured heat flow curves, denoted q_w and q_{hft}, show significantly reduced and delayed peaks compared to calculated heat flow, denoted q_{ss}.

Thermal Lag

One measure of dynamic thermal performance is thermal lag. Thermal lag is a measure of the response of indoor surface temperatures and heat flow to fluctuations in outdoor air temperatures. Lag is dependent on thermal resistance and heat storage capacity of the test specimen, since both of these factors influence the rate of heat flow.

Calibrated hot box thermal lag is quantified by two methods. In one measure, lag is calculated as the time required for the maximum or minimum specimen surface temperature on the metering chamber side to be reached after the maximum or minimum climatic chamber air temperature is attained. In the second measure, lag is calculated as the time required for the maximum or minimum heat flow rate, q_w, or q_{hft}, to be reached after the maximum or minimum heat flow rate based on steady-state predictions, q_{ss}, is attained. The second measure is illustrated in Fig. 9 for the NBS Test Cycle applied to Wall L. Both measures give similar results.

Average thermal lag was 6.5 h for the NBS Test Cycle applied to Wall L. The value determined using heat flux transducer data is the same as that determined from calibrated hot box test results.

Lag times of 3 to 15 h are generally beneficial for exterior walls. Walls with these lag times delay peak afternoon heat loads until cooler night hours. Thermal lags as low as 3 h are beneficial in delaying peak afternoon loads until cooler evening hours. These lower lag times are especially beneficial in commercial and industrial buildings that are vacated in the evening hours. The "lag effect" is also beneficial for passive solar applications.

Reduction in Amplitude

Reduction in amplitude is a second measure of dynamic thermal performance. Reduction in amplitude, as well as thermal lag, is influenced by both wall thermal resistance and heat storage capacity. Reduction in amplitude is dependent on the temperature cycle applied to the test specimen.

Reduction in amplitude is defined as the percent reduction in peak heat flow when compared to peak heat flow calculated using steady-state theory. Reduction in amplitude is illustrated in Fig. 9. Values for reduction in amplitude were calculated using the equation

$$A = [1 - (q' - \bar{q})/(q'_{ss} - \bar{q}_{ss})] \cdot 100 \tag{2}$$

where

A = reduction in amplitude, %,
q' = maximum or minimum heat flow through wall,
$\bar{q}$ = mean heat flow through wall,
q'_{ss} = maximum or minimum heat flow through wall predicted by steady-state analysis, and
$\bar{q}_{ss}$ = mean heat flow through wall predicted by steady-state analysis.

Average reduction in amplitude for heat flow measured by the calibrated hot box, q_w, is 47% for the NBS Temperature Cycle. Reduction in amplitude from heat flux transducer measurements is 58%.

Amplitudes for heat flux transducer data, q_{hft}, are generally not the same as those for calibrated hot box measurements, q_w [*12,13*]. Heat flow amplitudes differ because of the physical presence of the instrument mounted on a wall. A wall's thermal properties are locally altered by the heat flux transducer. In addition, heat flux transducer calibration using steady-state hot box results may not fully correct for dynamic effects of the instrument location.

Actual maximum heat flow through a wall is important in determining the peak energy load for a building envelope. Test results show that anticipated peak energy demands based on actual heat flow are less than those based on steady-state predictions for walls with thermal storage capacity [*1*]. As expected, calculations based on steady-state analysis overestimate peak heat flow for the dynamic temperature cycle applied to Wall L.

Total Heat Flow

Results of dynamic tests are also compared using measures of total heat flow through a specimen for a 24-h temperature cycle. Figure 9 can be used to illustrate total measured heat flow. The curve marked "q_w" is heat flow through the test wall measured by the calibrated hot box. Areas enclosed by the measured heat flow curve and the line for zero heat flow are total heat flow through a wall. The sum of the areas above and below the horizontal axis is total measured heat flow for a 24-h period. A similar procedure is used to calculate total heat flow for a 24-h period from measured heat flux transducer data, q_{hft}, and predictions based on steady-state analysis, q_{ss}.

Total heat flows for a 24-h period measured by the calibrated hot box, measured by heat flux transducers, and predicted by steady-state analysis, respectively are 129, 107, and 294 W · h/m^2 (40.9, 33.8, and 93.3 Btu/ft^2).

Total heat flow measured by the calibrated hot box is 44% of total heat flow calculated using steady-state analysis. The ratio of total measured heat flow to steady-state predictions, denoted the total heat flow ratio, depends on the climatic chamber air temperature cycle applied to the wall. Particularly for massive walls, greater reductions in actual heat flow, compared to steady-state predictions, occur for temperature cycles which produce heat flow reversals through a wall.

It should be noted that comparison of total measured heat flow values are limited to the specimen and dynamic cycle evaluated in this program. Results are for a particular diurnal test cycle and should not be arbitrarily assumed to represent annual heating and cooling loads. In addition, results are for an individual opaque wall assembly. As such, they are representative of only one component of the building envelope.

Comparisons with Other Concrete Walls

Dynamic heat transmission coefficients of thermal lag, reduction in amplitude, and total heat flow ratio are used to compare dynamic thermal response of alternative wall systems.

Thermal lag and reduction in amplitude are dependent on both thermal resistance, R, and heat storage capacity,

$$\rho c L$$

where

ρ = wall density, kg/m^3 (pcf),
c = wall specific heat, J/kg · K (Btu/lb · °F), and
L = wall thickness, m (ft).

Mass, ρL, is the predominant factor in determining heat storage capacity of most building materials.

For homogeneous walls, thermal lag and reduction in amplitude increase with an increase in M [15]:

$$M = \left(\frac{L^2/\alpha}{P}\right)^{1/2} = \left(\frac{(R)\cdot(\rho c L)}{P}\right)^{1/2} \tag{3}$$

where

L = wall thickness, m (ft),
α = thermal diffusivity, $k/\rho c$, m^2/s (ft^2/h),
k = thermal conductivity of wall, W/m · K (Btu/h · ft · °F),
ρ = wall density, kg/m^3 (pcf),
c = wall specific heat, J/kg · K (Btu/lb · °F),
R = wall resistance, m^2 · K/W (h · ft^2 · °F/Btu), and
P = period of dynamic cycle, h.

Table 8 presents values of M and dynamic heat transmission coefficients for Wall L and three other homogeneous concrete walls. Thermal lag, reduction in amplitude, and total heat flow ratio are for the NBS Temperature Cycle applied to each wall using the calibrated hot box. Thermal resistances used in Eq 3 to calculate M are for a wall mean temperature of 24°C (75°F) and are from measurements using CTL's calibrated hot box. Surface resistances are not included in resistances used in Eq 3.

TABLE 8—*Concrete wall comparisons.*

Wall Designation	Wall Type	Reference	Measured Properties								Calculated M
			L Thickness, mm (in.)	Unit Weight, kg/cu m (pcf)	Estimated Moisture Content, % ovendry wt.	R* Thermal Resistance, sq m·K/W (hr·sq ft·°F/Btu)	c** Specific Heat, J/kg·K (Btu/lb·°F)	Thermal Lag,*** hr	Amplitude Reduction,*** %	Total Heat Flow Ratio,*** %	
C1	Normal weight structural concrete with sand and gravel aggregate	7	211 (8.31)	2310 (144)	2	0.12 (0.71)	810 (0.19)	4.0	45	53	0.75
C2	Lightweight structural concrete with expanded shale aggregate	8	210 (8.28)	1630 (102)	9	0.31 (1.75)	960 (0.23)	5.5	54	48	1.09
L	Lightweight structural concrete with Macrolite™ aggregate	-	203 (8.00)	900 (56)	2	0.77 (4.4)	460 (0.11)	6.5	47	44	0.87
C3	Low density concrete with expanded perlite aggregate	9	216 (8.52)	740 (46)	10	1.00 (5.9)	750 (0.18)	8.5	61	39	1.20

* From calibrated hot box (ASTM: C976) test results at a wall mean temperature of 24°C (75°F). Values do not include surface film resistances.

** Measured using U.S. Army Corps of Engineers Method CRD-C124-73.

*** Measured using the NBS Dynamic Temperature Cycle.