Portland Cement Association

Research & Development Information

PCA R&D Serial No. 0880

Structural Thermal Break Systems for Buildings - Development and Properties of Concrete Systems

by Albert Litvin and Martha G. VanGeem

5420 Old Orchard Road
Skokie, Illinois 60077-1083
847.966.6200 Fax 847.966.9481

www.cement.org

ORNL/Sub/84-21006/2

STRUCTURAL THERMAL BREAK SYSTEMS FOR BUILDINGS - DEVELOPMENT AND PROPERTIES OF CONCRETE SYSTEMS

Final Report

by

Albert Litvin and Martha G. Van Geem

Report Prepared by

CONSTRUCTION TECHNOLOGY LABORATORIES, INC.
5420 Old Orchard Road
Skokie, Illinois 60077
Under Subcontract No. DE-AC05-84CE21006

Prepared for
Building Thermal Envelope Systems and Materials Program
Energy Division
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
Operated by
MARTIN MARIETTA ENERGY SYSTEMS INC.
for the
U.S. DEPARTMENT OF ENERGY
Under Contract No. DE-AC05-84OR21400

October 1988

CR8057
Doc. I.D. 0961b/0962b

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
NTIS price codes - Printed Copy: A05 Microfiche A01

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

STRUCTURAL THERMAL BREAK SYSTEMS FOR BUILDINGS - DEVELOPMENT AND PROPERTIES OF CONCRETE SYSTEMS

by

Albert Litvin and Martha G. Van Geem*

ABSTRACT

This report presents results from the second phase of a three phase program to investigate lightweight concrete systems for potential use as structural thermal breaks in buildings.

The primary objective of the project is to develop a portland cement concrete with sufficient thermal resistance and strength properties to serve as an effective structural thermal break in building envelopes. Desirable properties of the proposed concrete are a density of less than 50 pcf (800 kg/m^3), a compressive strength of 1000 to 1500 psi (6.9 to 10.3 MPa), and a thermal conductivity of about 1.5 Btu•in./hr•ft^2•°F (0.22 W/m•K). 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 145 pcf (2320 kg/m^3), a compressive strength in the range of 2500 to 6000 psi (17 to 41 MPa), and a thermal conductivity of 12 to 16 Btu•in./hr•ft^2•°F (1.7 to 2.3 W/m•K).

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 (see Reference 1).

The second phase of work, presented in this report, is the laboratory development and measurement of properties of the lightweight portland cement concrete. Work included materials selection and concrete mix development. Thermal and physical properties of the candidate concretes were measured on small-scale specimens. Data on concrete thermal conductivity, thermal diffusivity, specific heat, compressive strength, flexural strength, shear strength, splitting tensile strength, and modulus of elasticity are presented. Casting and surface finishing techniques for the most desirable mix are also described.

*Consultant and Senior Research Engineer, respectively, Construction Technology Laboratories, Inc., 5420 Old Orchard Road, Skokie, Illinois 60077 (312) 965-7500.

Data presented in this report indicate that the strength and weight requirements for the lightweight portland cement concrete have been met. Thermal conductivity of the newly developed lightweight concrete is about 1/10th that for normal weight concrete.

An additional project objective was to develop a polymer concrete with compressive strength of 3000 psi (21 MPa) or more and thermal conductivity of 1.0 Btu•in./hr•ft^2•°F (0.14 W/m•K) or less. This report describes polymer concrete mix development and concrete properties. The polymer concrete requirements have not yet been met. Additional work is needed to determine whether it is possible to fully meet these requirements.

EXECUTIVE SUMMARY

Project Description

A significant amount of energy is lost from conditioned environments of buildings through thermal bridges. Reduction of energy loss can be achieved by providing thermal break materials in place of high conductivity materials that create thermal bridges.

The purpose of this project is to investigate lightweight concrete systems for potential use as structural thermal breaks in buildings.

The program was conducted at Construction Technology Laboratories, Inc., (CTL). The project is 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).

A thermal break is an 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 the material has load-bearing capabilities.

The primary objective of this project is to develop a portland cement concrete with sufficient thermal resistance and strength properties to serve as an effective structural thermal break in building envelopes. The project goal is to develop a concrete with a density of less than 50 pcf (800 kg/m^3), a compressive strength of 1000 to 1500 psi (6.9 to 10.3 MPa), and a thermal conductivity of about 1.5 $Btu \cdot in./hr \cdot ft^2 \cdot °F$ (0.22 $W/m \cdot K$). The most commonly used concrete, normal weight concrete, has a density of approximately 145 pcf (2320 kg/m^3), a compressive strength in the range of 2500 to 6000 psi (17 to 41 MPa), and a thermal conductivity of 12 to 16 $Btu \cdot in./hr \cdot ft^2 \cdot °F$ (1.7 to 2.3 $W/m \cdot K$). Lightweight concretes have not been previously developed with the combination of low density and moderate strength proposed for this project.

Although it is envisioned that the proposed lightweight concrete 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 will combine the structural, thermal insulation, and heat storage capacity functions of exterior walls in one element. For many climates the concrete developed can be used as a complete wall system in low-rise buildings without additional insulation.

A secondary project objective is to develop a polymer concrete with sufficient thermal resistance and strength to serve as a structural thermal break material. Desired

properties of this material are a minimum compressive strength of 3000 psi (21 MPa) and a thermal conductivity less than 1 Btu•in./hr•ft^2•°F (0.14 W/m•K). The polymer concrete would be used to provide a thermal insulating layer adjacent to conventional construction materials whereas the portland cement concrete would be used either as an insulating layer or as an entire component such as a wall. Since polymer concrete is relatively expensive compared to portland cement concrete, the use of polymer concrete is anticipated to be limited to smaller building components.

The project is divided into five major tasks. This is the second of three project reports. The first report summarizes results of Task 1, which is a feasibility study to identify uses for the proposed lightweight portland cement concrete in buildings.*

This report summarizes results from Tasks 2, 3, and 4. Task 2 includes work to select materials and mix designs for the lightweight portland cement and lightweight polymer concretes. Physical and thermal properties of candidate concretes were determined in Task 3. Casting and surface finishing techniques for the most desirable mixes were developed in Task 4.

Task 5 includes measuring thermal performance of full-size wall assemblies constructed of the developed portland cement

---

* Larson, S. C., and Van Geem, M. G., "Structural Thermal Break Systems for Buildings - Feasibility Study," Oak Ridge National Laboratory Report No. ORNL/Sub/84-21006/1, Construction Technology Laboratories, Inc., Skokie, 1987, 88 pages.

concrete. Results from Task 5 will be presented in a future report.*

Portland Cement Concrete

The project objectives for the portland cement concrete were met using a newly developed aggregate from the 3M Company. The average compressive strength obtained with this aggregate was approximately 2000 psi (13.8 MPa), well in excess of the requirement, and very suitable for walls in low-rise buildings. The developed concrete has an air-dry unit weight of approximately 50 pcf (800 kg/m^3) and a measured thermal conductivity of 1.6 $Btu \cdot in./hr \cdot ft^2 \cdot °F$ (0.23 $W/m \cdot K$) at 75°F (24°C). Thermal conductivity of the lightweight concrete is 1/10th that for normal weight concrete.

Concrete thermal and physical properties were measured on small-scale specimens. Results are presented for thermal conductivity, thermal diffusivity, specific heat, compressive strength, flexural strength, shear strength, splitting tensile strength, and modulus of elasticity. Test results indicate the concrete is suitable for walls in low-rise buildings.

Two full-size walls were cast for subsequent testing in CTL's calibrated hot box facility. No significant problems were encountered in casting and consolidating these panels in a horizontal position. Thus an obvious use for the material would be in precast or tilt-up panel construction. Rheology of

---

* Van Geem, M. G., "Structural Thermal Break Systems for Buildings - Heat Transfer Characteristics of Lightweight Structural Concrete Walls," Oak Ridge National Laboratory Report No. ORNL/Sub/84-21006/3, Construction Technology Laboratories, Inc., Skokie, to be published.

the material indicates that consolidation in a vertically cast wall might be more difficult. However it was not within the project scope to investigate vertical casts.

Polymer Concrete

For the polymer concrete development, five polymer materials were investigated for use with the 3M aggregate. The best combination of weight and strength obtained was a unit weight of 50 pcf (800 kg/m^3) and compressive strength of 3020 psi (20.8 MPa). Thermal conductivity of the concrete was 1.4 $Btu \cdot in./hr \cdot ft^2 \cdot °F$ (0.21 W/m•K) at 75°F (24°C). Additional work is needed to determine whether it is possible to lower the thermal conductivity to meet target polymer concrete properties.

STRUCTURAL THERMAL BREAK SYSTEMS FOR BUILDINGS- DEVELOPMENT AND PROPERTIES OF CONCRETE SYSTEMS

by

Albert Litvin and Martha G. Van Geem*

INTRODUCTION AND OBJECTIVES

The purpose of this project is to investigate lightweight concrete systems for potential use as structural thermal breaks in buildings. A thermal break is a 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 the material has load bearing capabilities.

The primary project objective is to develop portland cement concrete with sufficient thermal resistance and strength properties to serve as an effective thermal break. The project goal is to develop a concrete with a density of less than 50 pcf (800 kg/m^3), a compressive strength of 1000 to 1500 psi (6.9 to 10.3 MPa), and a thermal conductivity of about 1.5 Btu•in./hr•ft^2•°F (0.22 W/m•K). Although it is envisioned that concrete with these properties could be used for many

*Consultant and Senior Research Engineer, respectively. Construction Technology Laboratories, Inc., 5420 Old Orchard Road, Skokie, Illinois 60077 (312) 965-7500.

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

A secondary project objective is to develop a polymer concrete with sufficient thermal resistance and strength to serve as a thermal break material. Desired properties of this material are a minimum compressive strength of 3000 psi (21 MPa) and a thermal conductivity less than 1 Btu•in./hr•ft^2•°F (0.14 W/m•K). The polymer concrete would be used to provide a thermal insulating layer adjacent to conventional construction materials whereas the portland cement concrete would be used either as an insulating layer or as an entire component such as a wall.

The objectives for the polymer concrete and portland cement concrete are similar. Because it is anticipated to be more expensive than portland cement concrete, polymer concrete would be used for relatively smaller building elements.

The program was conducted at Construction Technology Laboratories, Inc. (CTL). The project is sponsored jointly by the U.S. Department of Energy (DOE) Office of Building 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). Work was authorized by a contract signed September 25, 1984 by Walker K. Love. The DOE Project Manager is Dr. George E. Courville, ORNL.

SCOPE

The project is divided into five major tasks. This is the second of three project reports. The first report[1]* summarizes results of Task 1, which is a feasibility study to identify uses for the proposed lightweight portland cement concrete in buildings.

This report summarizes results from Tasks 2, 3, and 4. Task 2 includes work to select materials and mix designs for the lightweight portland cement and lightweight polymer concretes. Physical and thermal properties of candidate concretes were determined in Task 3. Casting and surface finishing techniques for the most desirable mixes were developed in Task 4.

Task 5 includes measuring thermal performance of full-size wall assemblies constructed of the developed portland cement concrete. Results from Task 5 will be published in a future report.[2]

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.

*Superscript numbers in parentheses refer to references listed at the end of this report.

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 145 pcf (2320 kg/m^3), and compressive strengths of approximately 2500 to 6000 psi (17 to 41 MPa) are common. High-strength normal weight concretes have been developed with strengths exceeding 15,000 psi (100 MPa).

Concretes in the 90 to 130 pcf (1440 to 2080 kg/m^3) range are known as structural lightweight aggregate concretes. These concretes have compressive strengths in the range of 2500 to over 9000 psi (17.2 to over 62.1 MPa), depending on materials, mix design, and other factors.

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

Concretes weighing 50 pcf (800 kg/m^3) or less are called insulating concretes. Current technology limits the compressive strengths of these concretes to about 600 psi (4.1 MPa).[3]

A second category of lightweight concretes is in the weight range of 50 to about 90 pcf (800 to about 1440 kg/m^3). 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 45

to 55 pcf (720 to 800 kg/m^3) 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.

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 dependent on the constituent aggregates, and to a lesser extent, the cement paste. Concrete with a unit weight of 50 pcf (800 kg/m^3) has a thermal conductivity of approximately 1.5 Btu•in./hr•ft^2•°F (0.22 W/m•K) while concrete with a unit weight of 140 pcf (2240 kg/m^3) has a thermal conductivity of approximately 16 Btu•in./hr•ft^2•°F (2.3 W/m•K). Generally, concrete conductivity increases exponentially with unit weight.

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 massive 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.

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 lowest unit weight. The concrete unit weight is limited by the need for sufficient structural capacity, because strength generally decreases with decreasing unit weight.

PORTLAND CEMENT CONCRETE

General

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 the aggregate volume is so high, its specific gravity greatly influences the weight of the concrete. While the 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.*

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 90 to 115 pcf (1400 to 1800 kg/m^3).

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.

Materials

The following materials were used for development of the portland cement concrete.

Portland Cement

One brand of Type 1 portland cement, available in the Chicago, Illinois area, was used throughout this investigation.

*The strength-to-weight ratio is the ratio of the concrete's compressive strength to its unit weight.

The cement met requirements of ASTM Designation: C 150, "Specification for Portland Cement."[4] Details on portland cement composition are given in Appendix A.

Aggregates

A number of lightweight aggregates were obtained and included in preliminary mixes to determine their possible suitability for this program.

Livlite*: This is an expanded clay aggregate produced by Tombigbee Lightweight Aggregate Co., Livingston, Alabama. Livlite, shown in Fig. 1, was used to advantage in a previous CTL investigation because of its excellent strength-to-weight relationship.

Tufflite: This is naturally occurring volcanic pumice aggregate mined by Arizona Tufflite, Inc. of Glendale, Arizona. Tufflite, shown in Fig. 2, is a highly absorptive aggregate being successfully used to produce moderate strength and weight concrete at low cost in southwestern portions of the United States.

Liapor: This is an expanded shale aggregate manufactured by Liapor Company of Hollerndorf, West Germany. Liapor, shown in Fig. 3, is well-known in the European lightweight concrete industry as a material capable of producing high strength-to-weight ratio concretes.

Leca: This is an expanded shale aggregate manufactured by A-S Norsk Leca of Oslo, Norway. Leca, shown in Fig. 4, is well-known in Europe as a relatively light weight material

*Product names used in this report may be trademarked.

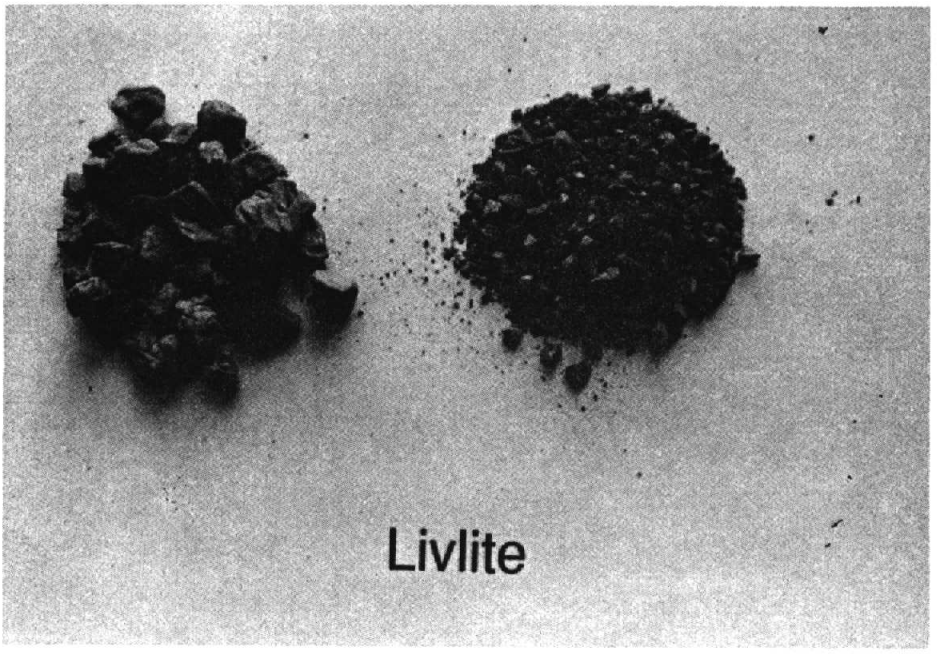


Fig. 1 Livlite

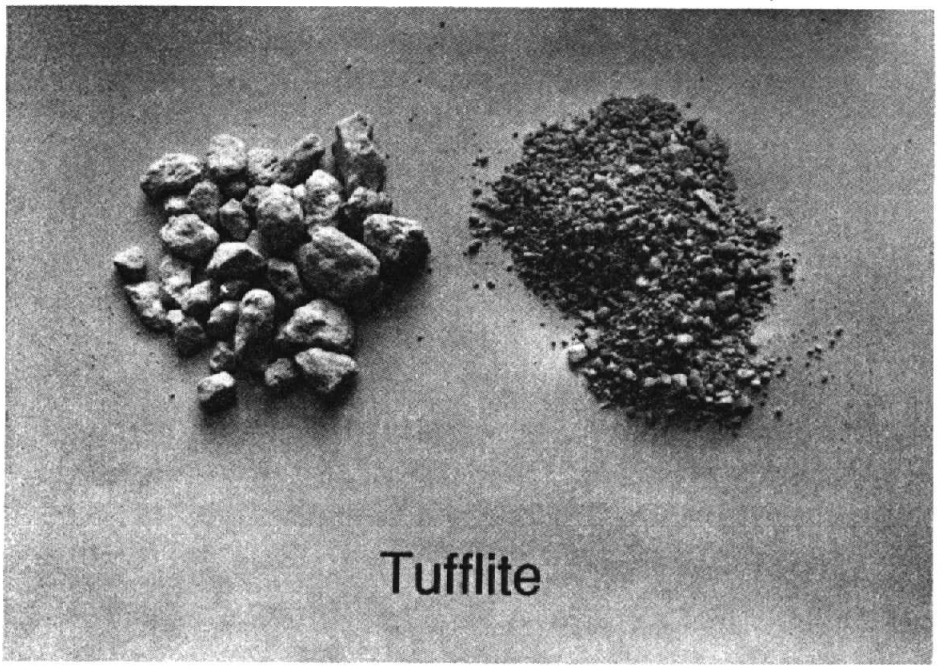


Fig. 2 Tufflite

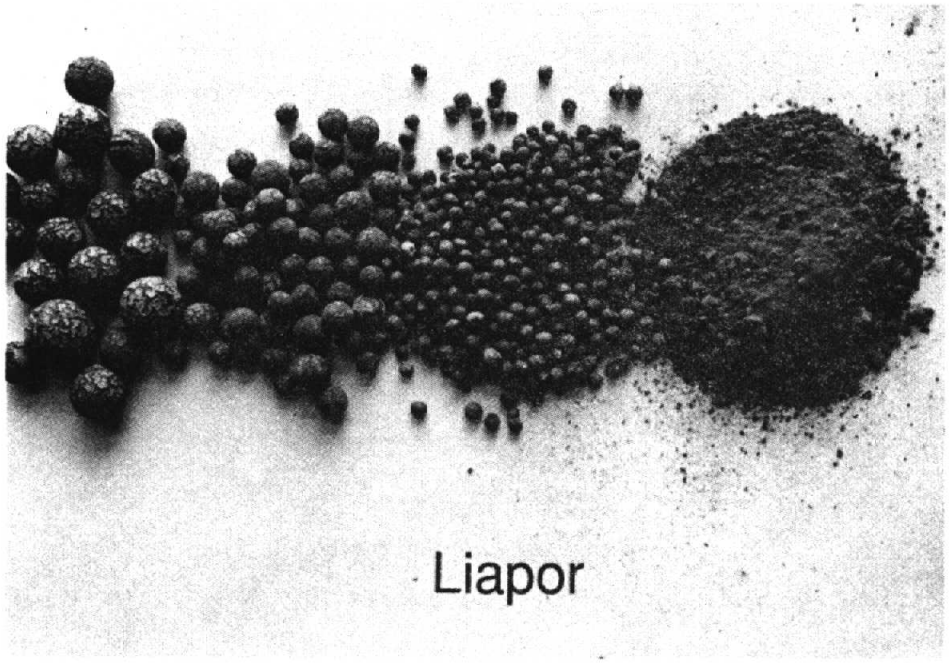


Fig. 3 Liapor

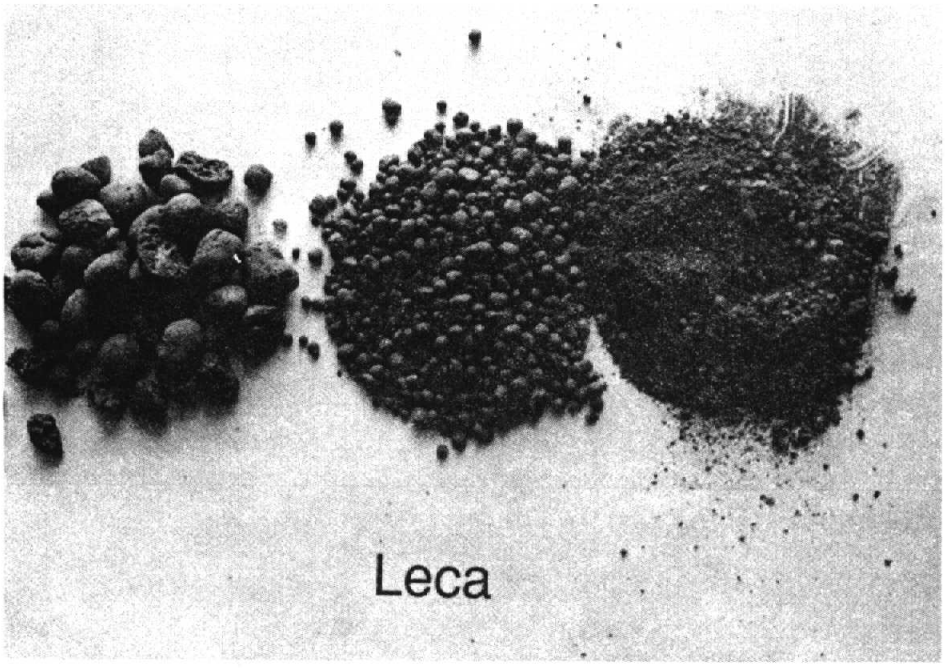


Fig. 4 Leca

capable of achieving moderate strength concretes. Both Liapor and Leca are produced by grinding and pelletizing shales or clays, and firing in a rotary kiln. Thus, these aggregates are spherical as compared to Tufflite and Livlite which are irregularly shaped.

3M Macrolite Ceramic Spheres: This aggregate, shown in Fig. 5, 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; 1/2 in. to No. 4 (12.7 to 4.75 mm), and No. 4 to No. 50 (4.75 mm to 300 μm). A product information sheet for 3M Macrolite Ceramic Spheres is included as Appendix B.

PQ Inorganic Microspheres: This is a fine aggregate, all passing the No. 8 screen (2.36 mm), and was supplied by the PQ Corporation of Philadelphia, PA. PQ Inorganic Microspheres, shown in Fig. 6, have the lowest specific gravity of all the aggregates utilized in this investigation, and were used as fine aggregates in some mixes in an attempt to lower unit weight.

Fillite: This material, furnished by Fillite USA, Inc. of Huntington, West Virginia, is described as hollow alumina silica microspheres. The particles are similar in size and

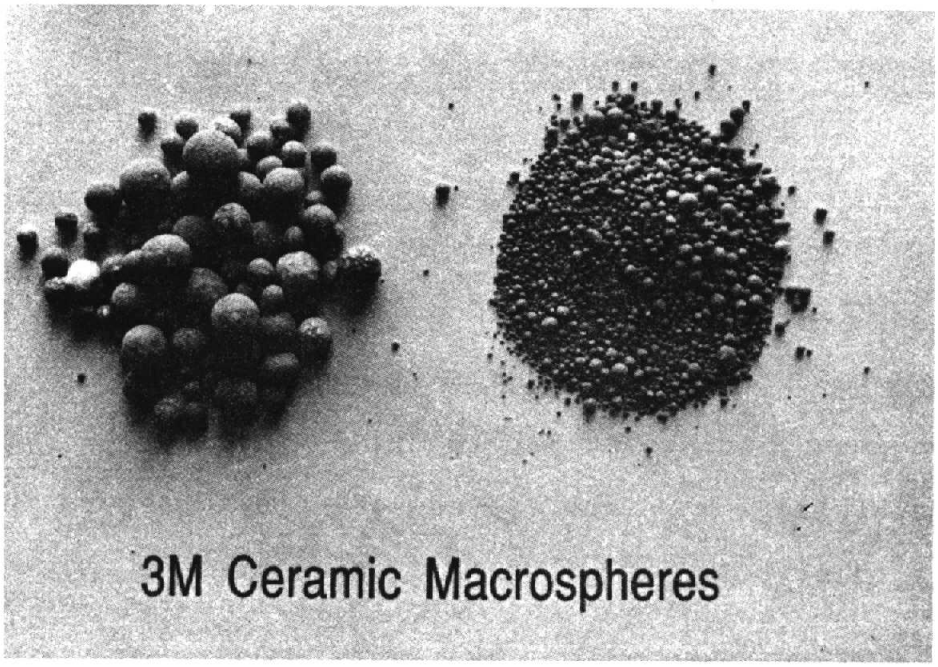


Fig. 5 3M Macrolite Ceramic Spheres

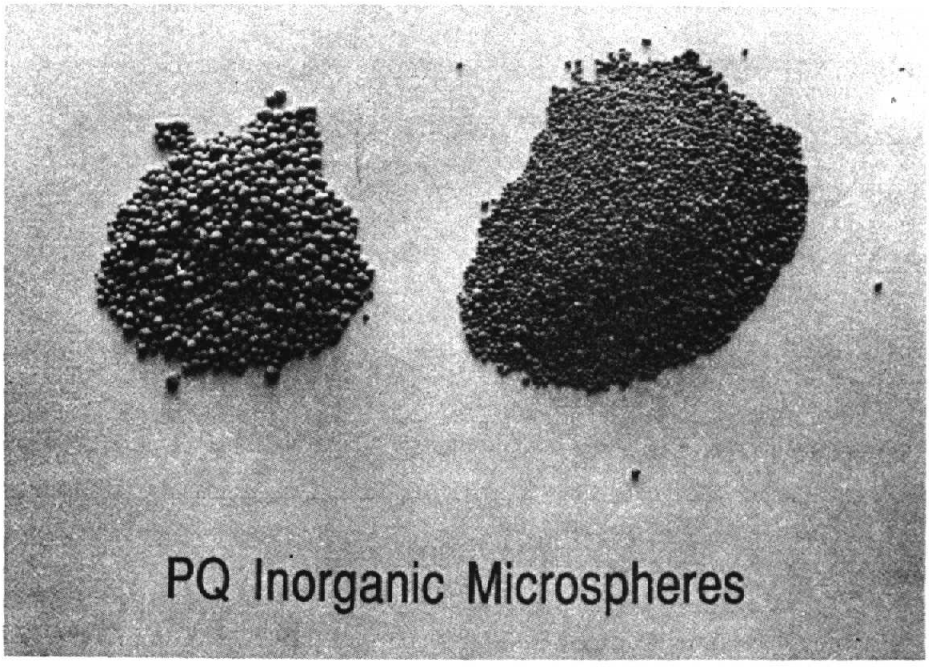


Fig. 6 PQ Inorganic Microspheres

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 range of size.

Mineral Admixture

Silica fume: Silica fume, shown in Fig. 7, is a by-product from the production of silicon or ferro-silican metal. It has a very high percentage of silica and is extremely fine, about 60 times finer than portland cement. It is a very efficient pozzolanic material, and was used in this program to increase the strength of mixes containing relatively low cement contents. The silica fume used in this program was furnished by Hanna Mining Co., Wenatchee, Washington.

Chemical Admixtures

WRDA: This is a water-reducing admixture manufactured by the Construction Products Division of W. R. Grace & Co. It was used to offset any increased water that might have been required by use of the very fine silica fume.

Vinsol resin: A 2% solution of laboratory prepared vinsol resin air-entraining agent was used in all mixes. Air entrainment in concrete mixes increases workability and provides resistance to possible damage from cycles of freezing and thawing.

Mightly 150: This superplasticizer, manufactured by Boremco Specialty Chemicals, was used in a few mixes in an effort to increase strength by reduction of water-cement ratio.

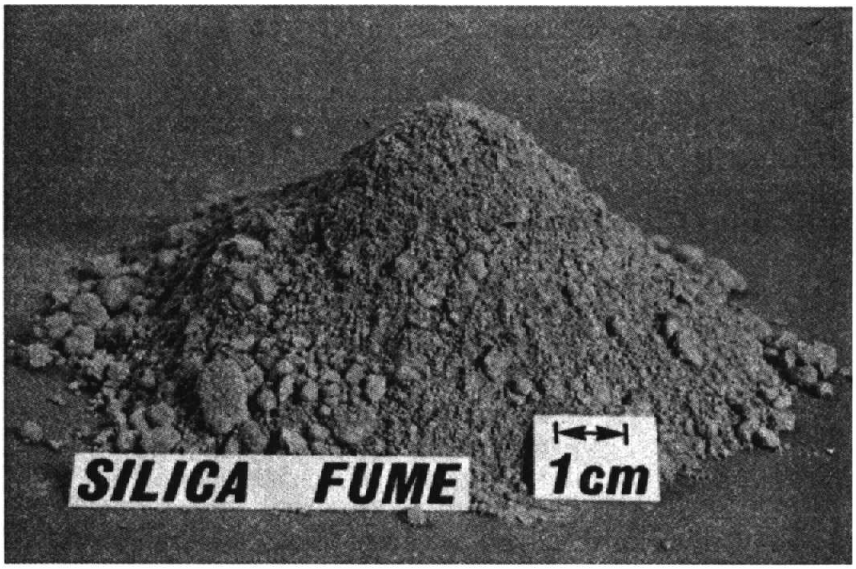


Fig. 7 Silica Fume

Preliminary Mix Development

Concrete mixes were made using all of the aggregates, singly or in combination, listed in the previous section. 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. Table 1 shows the number of mixes made with each aggregate or combinations of aggregates. 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 had the highest strength-to-weight ratio and had the best chance of meeting the program objectives. Therefore, the most number of mixes were made with this aggregate to optimize the strength-to-weight relationship and to provide test specimens for further testing.

Table 2 presents detailed mix designs and properties for each mix summarized in Table 1.

Most of the 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.

Fresh concrete unit weights were determined in accordance with ASTM Designation: C 138, "Standard Test Method for Unit Weight, Yield, and Air Content (Gravimetric) of Concrete."[4]

TABLE 1 - PORTLAND CEMENT CONCRETE UNIT WEIGHTS AND COMPRESSIVE STRENGTHS[1]

Aggregate	No. of Mixes	Unit Weight, pcf (kg/m^3)		Compressive Strength,[4] psi (MPa)		Strength-to-Weight Ratio[6], psi/pcf (kPa/(kg/m^3))
		Fresh[2]	28 day[3]	7 day[5]	28 day[3]	
Project Objective	—	—	50 (800)	—	1500 (10.3)	30 (12.9)
Tufflite	1	81.2 (1299)	56.1 (898)	490 (3.4)	850 (5.9)	15.2 (6.6)
Tufflite & Fillite	1	79.9 (1278)	58.8 (941)	610 (4.2)	1020 (7.0)	17.3 (7.4)
Liapor	3	62.8 (1005)	56.1 (898)	780 (5.4)	1160 (8.0)	20.7 (8.9)
Liapor & Fillite	4	66.5 (1064)	60.1 (962)	1190 (8.2)	1600 (11.0)	26.6 (11.4)
Liapor, Fillite & PQ Microspheres	1	63.1 (1010)	56.0 (896)	1230 (8.5)	1380 (9.5)	24.6 (10.6)
Liapor, Fillite & 3 M Macrolite	2	56.0 (896)	51.8 (829)	1550 (10.7)	1680 (11.6)	32.4 (14.0)
Tufflite & Liapor	1	69.2 (1107)	63.4 (1014)	1300 (9.0)	1590 (11.0)	25.1 (10.8)
Livlite & Liapor	1	69.8 (1117)	62.3 (997)	1170 (8.1)	1480 (10.2)	23.8 (10.2)
Livlite	1	79.7 (1275)	67.5 (1080)	1150 (7.9)	2170 (15.0)	32.1 (13.9)
Livlite & Fillite	1	75.8 (1213)	60.6 (970)	580 (4.0)	1500 (10.3)	24.8 (10.6)
Leca	1	66.4 (1062)	58.8 (941)	600 (4.1)	980 (6.8)	16.7 (7.2)
3M Macrolite & Fillite	8	49.4 (790)	48.7[7] (779)	1400[8] (9.6)	1780[9] (12.3)	36.6 (15.8)

(1) Values are averages for the number of mixes specified, unless otherwise noted.
(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.
(7) Average for 5 mixes.
(8) Average for 4 mixes.
(9) Average for 7 mixes.

TABLE 2 - PORTLAND CEMENT CONCRETE MIXES AND PROPERTIES

Mix Designation	Materials (1)										Fresh Concrete Properties		Hardened Concrete Properties		
	Coarse Aggregate		Fine Aggregate		Fillite	Cement	Mineral Admixture		Chemical Admixture		Fresh Unit Weight, (3) pcf (kg/cu m)	Air Content, (1) %	Air Dry Unit Weight, (4) pcf (kg/cu m)	Compressive Strength, (5) psi (MPa)	
	Type	Size, In. (mm)	Type	Maximum Size, Sieve No. (mm)	Nominal Amount, lb per cu yd (kg per cu m)	Nominal Content, lb per cu yd (kg per cu m)	Type	Nominal Amount, lb per cu yd (kg per cu m)	Water-Reducing Admixture	Water-Cementitious Ratio, (2) by weight				7 days (6)	28 days (4)
LP-1	Liapor	3/8-1/8 (9.5-3.2)	Liapor	-4 (12) (-4.75)	—	400 (238)	—	—	—	0.46	64.5 (1032)	7.5	56.1 (898)	550 (3.8)	850 (5.9)
PU-1	Tufflite	1/2-1/8 (12.7-3.2)	Tufflite	-4 (-4.75)	—	400 (238)	—	—	—	0.48	81.2 (1299)	6.7	56.1 (898)	490 (3.4)	850 (5.9)
LI-1	Livlite	1/2-No.4 (12.7-4.75)	Livlite	-4 (-4.75)	—	400 (238)	—	—	—	0.43	79.7 (1275)	8.8	67.5 (1080)	1150 (7.9)	2170 (15.0)
PU-2	Tufflite	1/2-1/8 (12.7-3.7)	Tufflite	-4 (-4.75)	31 (18)	300 (178)	Silica Fume	67 (40)	—	0.63	79.9 (1278)	6.0	58.8 (941)	610 (4.2)	1020 (7.0)
LI-2	Livlite	1/2-1/8 (12.7-3.2)	Livlite	-4 (-4.75)	31 (18)	300 (178)	Silica Fume	67 (40)	—	0.68	75.8 (1213)	8.5	60.6 (970)	580 (4.0)	1500 (10.3)
LE-1	Leca	3/8-1/8 (9.5-3.2)	Leca	-8 (-2.36)	—	400 (238)	—	—	—	—(13)	66.4 (1062)	>12.0	58.8 (941)	600 (4.1)	980 (6.8)
LP-2	Liapor	3/8-1/8 (9.5-3.2)	Liapor	-4 (-4.75)	34 (20)	400 (238)	Silica Fume	40 (24)	—	0.45	66.6 (1066)	6.0	59.8 (957)	1420 (9.8)	1600 (11.0)
A-1 (7)	Liapor	3/8-1/8 (9.5-3.2)	Liapor	-4 (-4.75)	—	450 (268)	—	—	—	0.66	60.9 (974)	>9.0	55.9 (894)	1150 (7.9)	1510 (10.4)
A-2 (7)	Tufflite	1/2-1/8 (12.7-3.2)	Liapor	-4 (-4.75)	—	450 (268)	—	—	—	0.74	69.2 (1107)	7.4	63.4 (1014)	1300 (9.0)	1590 (11.0)
	Liapor	1/4-1/8 (6.4-3.2)													
A-3 (7)	Livlite	1/2-1/8 (12.7-3.2)	Liapor	-4 (-4.75)	—	450 (268)	—	—	—	0.60	69.8 (1117)	>9.0	62.3 (997)	1170 (8.1)	1480 (10.2)
	Liapor	1/4-1/8 (6.4-3.2)													
LP-3	Liapor	3/8-1/8 (9.5-3.2)	Liapor	-4 (-4.75)	—	450 (268)	—	—	—	0.31	62.9 (1006)	~12	56.2 (899)	640 (4.4)	1110 (7.6)
LP-4	Liapor	3/8-1/8 (9.5-3.2)	Liapor	-4 (-4.75)	47 (28)	425 (253)	Silica Fume	25 (15)	—	0.44	61.7 (987)	9.0	55.4 (886)	780 (5.4)	1390 (9.6)
LP-5	Liapor	3/8-1/8 (9.5-3.2)	Liapor	-4 (-4.75)	47 (28)	425 (253)	Silica Fume	25 (15)	Mighty 150	0.28	70.9 (1134)	~6	64.4 (1030)	1370 (9.4)	1830 (12.6)
LP-5X	Liapor	3/8-1/8 (9.5-3.2)	Liapor	-4 (-4.75)	47 (28)	425 (253)	Silica Fume	25 (15)	Mighty 150	0.30	66.9 (1070)	~10	60.9 (974)	1180 (8.1)	1570 (10.8)

TABLE 2 (cont.) - PORTLAND CEMENT CONCRETE MIXES AND PROPERTIES

Mix Designation	Materials (1)										Fresh Concrete Properties		Hardened Concrete Properties		
	Coarse Aggregate		Fine Aggregate		Fillite	Cement	Mineral Admixture		Chemical Admixture		Fresh Unit Weight, (3) pcf (kg/cu m)	Air Content, (1) %	Air Dry Unit Weight, (4) pcf (kg/cu m)	Compressive Strength, (5) psi (MPa)	
	Type	Size, in. (mm)	Type	Maximum Size, Sieve No. (mm)	Nominal Amount, lb per cu yd (kg per cu m)	Nominal Content, lb per cu yd (kg per cu m)	Type	Nominal Amount, lb per cu yd (kg per cu m)	Water-Reducing Admixture	Water-Cementitious Ratio, (2) by weight				7 days (6)	28 days (4)
LP-6	Liapor	3/8-1/8 (9.5-3.2)	Liapor PQ	-4 (-4.75) -8 (-2.36)	34 (20)	400 (238)	Silica Fume	40 (24)	—	0.50	63.1 (1010)	3.5	56.0 (896)	1230 (8.5)	1380 (9.5)
LP-7	Liapor	3/8-1/4 (9.5-6.4)	3M	4 - 50 (4.75-0.30)	35 (21)	400 (238)	Silica Fume	40 (24)	Jimo	0.51	55.3 (885)	6.0	51.9 (830)	1410 (9.7)	1640 (11.3)
LP-8	Liapor	3/8-1/4 (9.5-6.4)	3M	4 - 50 (4.75-0.30)	34 (20)	425 (253)	Silica Fume	40 (24)	Jimo	0.48	56.7 (907)	4.5	51.7 (827)	1690 (11.6)	1720 (11.9)
3M-1 (7)	3M	1/2-No. 4 (12.7-4.75)	3M	4 - 50 (4.75-0.30)	34 (20)	400 (238)	Silica Fume	40 (24)	WRDA	0.55	48.0 (768)	— (14)	46.8 (749)	1220 (8.4)	1180 (8.1)
3M-2 (7)	3M	1/2-No. 4 (12.7-4.75)	3M	4 - 50 (4.75-0.30)	34 (20)	425 (253)	Silica Fume	40 (24)	WRDA	0.56	48.7 (779)	— (14)	47.7 (763)	1050 (7.2)	1320 (9.1)
3M-A (7)	3M	1/2-No. 4 (12.7-4.75)	3M	4 - 50 (4.75-0.30)	34 (20)	400 (238)	Silica Fume	40 (24)	WRDA	0.62	50.1 (802)	— (14)	49.9 (798)	1690 (11.6)	2140 (14.7)
3M-B (7)	3M	1/2-No. 4 (12.7-4.75)	3M	4 - 50 (4.75-0.30)	33 (20)	450 (268)	Silica Fume	45 (27)	WRDA	0.52	49.5 (792)	— (14)	— (13)	1650 (11.4)	2450 (16.9)
3M-C (7,8)	3M	1/2-No. 4 (12.7-4.75)	3M	4 - 50 (4.75-0.30)	33 (20)	425 (253)	Silica Fume	43 (26)	WRDA	0.54	47.3 (757)	— (14)	48.7 (779)	— (13)	1940 (13.4)
3M-CX (7,9)	3M	1/2-No. 4 (12.7-4.75)	3M	4 - 50 (4.75-0.30)	33 (20)	425 (253)	Silica Fume	43 (26)	WRDA	0.52	50.4 (806)	— (14)	49.8 (797)	— (13)	1800 (12.4)
3M-CYT (7, 10)	3M	1/2-No. 4 (12.7-4.75)	3M	4 - 50 (4.75-0.30)	33 (20)	425 (253)	Silica Fume	43 (26)	WRDA	0.53	50.8 (813)	— (14)	— (13)	— (13)	— (13)
3M-CY (7,11)	3M	1/2-No. 4 (12.7-4.75)	3M	4 - 50 (4.75-0.30)	33 (20)	425 (253)	Silica Fume	43 (26)	WRDA	0.52	50.4 (806)	— (14)	—(13)	— (13)	1650 (11.4)

(1) A 2% solution of vinsol resin air-entraining agent was used in all mixes.
(2) The water-cement ratio shown is the amount of water added to the mix divided by the amount of added cement and silica fume.
(3) ASTM Designation: C 138, "Standard Test Method for Unit Weight, Yield, and Air Content (Gravimetric) of Concrete".
(4) Measured on 4x8-in. (100x200-mm) and 6x12-in. (150x300-mm) cylinders moist-cured 7 days at 73.4±3°F (23±1.7°C) and 100% RH, and then air-dried at 73.4±3°F (23±1.7°C) and 50±5% RH for the remaining 21days.
(5) ASTM Designation: C 39, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens".
(6) Measured on 4x8-in. (100x200-mm) and 6x12-in. (150x300-mm) cylinders moist-cured at 73.4±3°F (23±1.7°C) and 100% RH for 7 days.
(7) These mixes use dry aggregate.
(8) Trial mix for Wall No. 1.
(9) Average of 10 batches used for Wall No. 1.
(10) Trial mix for Wall No. 2.
(11) Average of 10 batches used for Wall No. 2.
(12) This notation denotes all material passed through the No. 4 sieve.
(13) Not available.
(14) Air meter could not measure air in these mixes.

Air content was measured in accordance with ASTM Designation C 173 "Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method."[4]

Seven and 28-day compressive strengths were measured in accordance with ASTM Designation: C 39, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens."[4] Compressive strengths were measured on 4x8-in. (100x200-mm)* and 6x12-in. (150x300-mm) cylinders. Although strength tests are generally performed on 6x12-in. (150x300-mm) cylinders, this program also used 4x8-in. (100x200-mm) cylinders to increase the number of cylinders made per concrete batch. For the project mixes, compressive strengths for the two cylinder sizes were generally comparable.

Seven-day compressive strengths were measured on cylinders moist-cured at 73.4±3°F (23±1.7°C) and 100% RH for 7 days. Twenty-eight-day compressive strengths were measured on cylinders moist-cured 7 days at 73.4±3°F (23±1.7°C) and 100% RH, and then air-dried at 73.4±3°F (23±1.7°C) and 50±5% RH for the remaining 21 days.

The development of mix designs in the range of strengths and weights desired involved a series of compromises. For example, to obtain lighter weight concrete it is desirable to use more of the larger sizes of aggregate which generally have lower specific gravities than the smaller sizes. However, this results in a harsher, less workable concrete. Most fine

*Cylinder dimensions are expressed as diameter by height.

aggregates were lacking in material passing the No. 50 screen (300 μm). Therefore, Fillite was utilized as a relatively lightweight material to replace some of the missing fine sizes, and because of its spherical shape, to increase workability. The use of more cement could result in more workable mixes and higher strength. However, cement has the highest specific gravity (3.15) of any ingredient in the concrete. Cement content must be kept to a minimum to reduce concrete weight.

To compensate for loss in workability and strength due to reduced cement content, it was decided to add silica fume, an extremely fine, highly active pozzolan. Because of its fineness, the use of silica fume usually increases the mixing water requirement of concrete, thus increasing water-cement ratio and lowering strength. This is normally overcome by use of superplasticizers which allow a considerable reduction in mixing water. Superplasticizers were tried in several mixes (not included in Tables 1 and 2). However, it was the judgment of the principal investigator that workability was poor and that such use was counterproductive. Instead, use was made of a standard water reducing admixture. This resulted in moderate water reduction while maintaining workability.

Values shown in Table 1 for the mixes containing 3M Macrolite are averages of unit weights and compressive strengths obtained on 8 mixes. For individual mixes, as shown in Table 2, fresh unit weights ranged from 48.0 to 50.8 pcf (768 to 813 kg/m^3), and 28-day compressive strengths ranged from 1180 (the first mix) to 2450 psi (8.1 to 16.9 MPa).

Part of the difficulty in obtaining consistent results has been in the variability of the 3M aggregate. Aggregate was received in a number of shipments. These varied in specific gravity from 0.83 to 0.88 for the coarse, and 0.45 to 0.70 for the fine sizes. Gradation of the aggregate also varied. Although the material was shipped in two sizes, 1/2 in. to #4 (13 to 4.75 mm) and #4 to #50 (4.75 mm to 300 μm), the manufacturer's screening operation was not well controlled. One shipment of coarse aggregate contained a large percentage of material close to 1/2 in. (13 mm) in size; another contained a large percentage close to the No. 4 (4.75-mm) size. One shipment of coarse aggregate contained considerable material passing the #4 screen (4.75 mm). The variability of aggregate properties is attributed to its manufacture in laboratory size equipment, much of which is manually controlled. It is expected that commercial production methods and equipment will result in a more uniform product. It has been demonstrated, however, that the material even as received for this program is capable of producing concrete that will satisfy the requirements of this program.

Final Mix Design

Based on the criteria discussed in previous sections, the mix shown in Table 3 was developed and was used for determining various concrete physical and thermal properties and for casting two full-size wall panels for determination of thermal properties. The same volumetric mix design was used for both

TABLE 3 - FINAL PORTLAND CEMENT CONCRETE MIX DESIGN

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

*Air content estimated at 6%.

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 50 pcf (800 kg/m^3).

Concrete Mix Designations 3M-CX and 3M-CY from Table 2 are the mixes for Wall Nos. 1 and 2, respectively, listed in Table 3.

Properties of Fresh Concrete

Ten 5-1/2 cu ft (0.156 m^3) batches were made for casting each of the two wall panels. Average fresh unit weight of the 10 batches for each of the two walls was 50.4 pcf (806 kg/m^3). However, the range in unit weights was 48.1 to 55.9 pcf (770 to 894 kg/m^3) for Wall No. 1 and 48.4 to 52.8 pcf (774 to 845 kg/m^3) for Wall No. 2.

The usual measurements taken on fresh concrete are slump (ASTM Designation: C143, Slump of Portland Cement Concrete), unit weight (ASTM Designation: C138, Unit Weight, Yield, and Air Content (Gravimetric) of Concrete), and air content (ASTM Designation: C138). Unit weight was determined on each batch and the range in results were reported in the preceding paragraph.

Initially, attempts were made to measure slump. However, mixes considered to be workable, by visual observation, had slumps less than 1 in. (25 mm). Since this concrete is 1/3 the weight of normal weight concrete, it is expected that it would slump much less than normal weight concrete of comparable

workability. This concrete cannot be used at conventional levels of slump (3 to 5 in.) as segregation would occur; the very lightweight aggregate would separate from the much heavier cement-water paste. It was decided that slump measurements on these mixes were meaningless and they were discontinued. Mixes were made to a consistency that was determined by visual observation to be "workable" and capable of being consolidated without segregation. Using visual observations as a method of mix acceptance criteria may not give as consistent results as control measurements used for normal weight concrete.

Measurements of air content of the fresh concrete were unreliable. While reasonable air contents of 5 to 7% were measured on the earlier mixes with other aggregates, these values were not obtained on the 3M Macrolite mixes using the same amount of air-entraining agent. The volumetric equipment, used for lightweight aggregate concrete, indicated air contents of under 2%. Since the appearance of the concrete indicated a much higher level of air entrainment, linear traverse measurements were later made to determine air content of the hardened concrete. These measurements, also, were difficult to make because of the presence of Fillite aggregate in the concrete. Fillite particles are about the same size as entrained air and can be easily identified (erroneously) as air bubbles. With a very careful air void analysis, and making allowances for the Fillite in the mix, the air content in the hardened concrete was estimated at 7 to 9%.

Since slump and air content measurements were not reliable methods of mix control, the 20 batches made for the two full-size walls used slight adjustments of air-entraining admixture and mixing water to control unit weight and workability. These methods of control proved to be quite satisfactory.

To provide test specimens for measurements of hardened concrete properties, the fresh concrete was consolidated into the required molds using a vibrating table. Rodding was not applicable as the rod would leave holes without properly consolidating the concrete.

Properties of Hardened Concrete

Selected physical and thermal properties were measured on specimens cast from six concrete mixes using 3M Macrolite as aggregates. Figure 8 shows a section through a 4-in. diameter (100-mm) cylinder of the concrete.

Four of the six mixes represent those used in the two full-size walls. Two of the mixes, denoted 3M-A and 3M-B, are development mixes very similar to those used for the panel castings and are presented in Table 4. Not all properties were determined on all mixes cast.

Unless otherwise noted, all reported values are the average of results from three test specimens.

Strength

Table 5 shows results from tests to determine compressive strength (ASTM Designation: C 39[4]), splitting-tensile

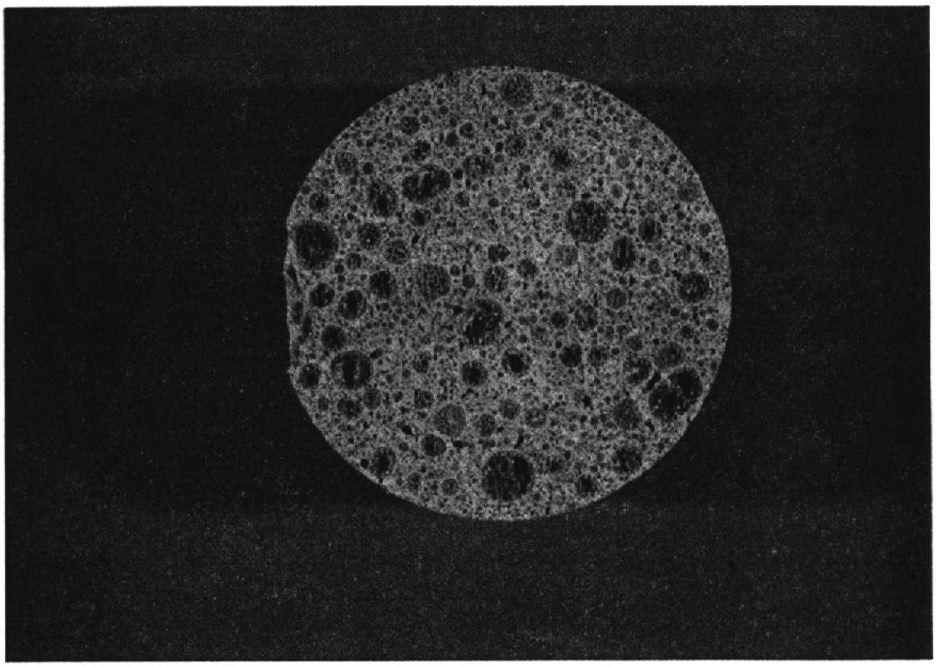


Fig. 8 Cross Section of a 4x8-in. (100x200-mm) Concrete Cylinder Made with 3M Macrolite Aggregate

TABLE 4 - MIX DESIGNS 3M-A AND 3M-B FOR SPECIMENS USED TO DETERMINE PHYSICAL AND THERMAL PROPERTIES

Material	Quantities per cu yd (0.765 m^3) of Concrete	
	Mix 3M-A	Mix 3M-B
Type I Portland Cement	349 lb (207 kg)	380 lb (226 kg)
Silica Fume	35 lb (21 kg)	38 lb (23 kg)
Water	240 lb (143 kg)	217 lb (129 kg)
3M Macrospheres 1/2" to No. 4 (12.7 to 4.75 mm)	288 lb (171 kg)	257 lb (153 kg)
No. 4 to No. 50 (4.75 to 0.30 mm)	411 lb (244 kg)	416 lb (247 kg)
Fillite	29 lb (17 kg)	28 lb (17 kg)
Vinsol Resin, 2.0% Solution	3.0 ml/lb cement (6.6 ml/kg cement)	3.5 ml/lb cement (7.7 ml/kg cement)
WRDA	2.07 ml/lb cement (4.55 ml/kg cement)	2.07 ml/lb cement (4.55 ml/kg cement)

TABLE 5 - STRENGTH PROPERTIES OF HARDENED CONCRETE

Mix No.	Compressive Strength,(1) psi (MPa)		Splitting Tensile Strength,(2) psi (MPa)		Modulus of Rupture,(3) psi (MPa)		Shear Strength,(4) psi (MPa)		Modulus of Elasticity,(5) 10^6psi (MPa)
	7 days(6)	28 days(7)	7 days(6)	28 days(7)	7 days(6)	28 days(7)	7 days(6)	28 days(7)	28 days(7)
3M-A	1690 (11.6)	2140 (14.7)	195 (1.3)	130 (0.9)	260 (1.8)	240 (1.7)	300 (2.1)	275 (1.9)	--
3M-B	1650 (11.4)	2450 (16.9)	175 (1.2)	130 (0.9)	250 (1.7)	260 (1.8)	275 (1.9)	310 (2.1)	--
3M-C	--	1940 (13.4)	--	--	--	--	--	--	0.927 (6390)
3M-CX	--	1800 (12.4)	--	155 (1.1)	--	--	--	255 (1.8)	1.086 (7480)
3M-CYT	--	--	--	--	--	--	--	--	--
3M-CY	--	1650 (11.4)	--	130 (0.9)	--	--	--	205 (1.4)	0.786 (5420)
Esti-mated	--	--	--	--	--	--	--	--	0.520(8) (3600)

(1) ASTM Designation: C39.
(2) ASTM Designation: C496.
(3) ASTM Designation: C78, also called flexural strength.
(4) PCA Method, described in text.
(5) ASTM Designation: 469.
(6) Seven-day strengths were measured on cylinders moist-cured at 73.4±3°F (23±1.7°C) and 100% RH for 7 days.
(7) Twenty-eight day strengths were measured on cylinders moist-cured 7 days at 73.4±3°F (23±1.7°C) and 100% RH, and then air-dried at 73.4±3°F (23±1.7°C) and 50±5% RH for the remaining 21 days.
(8) Estimated using method in Section 8.5.1 of Reference 5, using a unit weight of 50 pcf (80 kg/m^3) and a compressive strength of 1990 psi (13.7 kg/m^3).

strength (ASTM Designation: C 496[4]), modulus of rupture (ASTM Designation: C 78[4]), and modulus of elasticity (ASTM Designation: C 469[4]). Seven-day strengths were measured on cylinders moist-cured at 73.4±3°F (23±1.7°C) and 100% RH for 7 days. Twenty-eight-day strengths were measured on cylinders moist-cured 7 days at 73.4±3°F (23±1.7°C) and 100% RH, and then air-dried at 73.4±3°F (23±1.7°C) and 50±5% RH for the remaining 21 days.

Shear strength tests were performed on 4x8-in. (100x200-mm) concrete cylinders grouted into a special jig that allowed a direct shear force to be applied to each cylinder. The load was applied uniformly around one-half the circumference of the cylinder. Load was applied at a rate of 200 lb/minute (890 N/minute) until failure occurred.

Compressive strengths, modulus of elasticities, and splitting tensile strengths were determined on both 6x12-in. (150x300-mm) and 4x8-in. (100x200-mm) cylinders. Flexural strength was determined on 3x3x11-1/4-in. (75x75x285-mm) prisms.

The strength-to-weight relationship for this concrete is remarkable considering that the unit weight is only 50 pcf (800 kg/m^3) and the concrete is moist-cured for only 7 days. A comparison can be made with other moist-cured concretes of the same unit weight. Cellular concrete and perlite or vermiculite concrete with a 50 pcf (800 kg/m^3) unit weight would be expected to have a compressive strength of about 500 to 600 psi (3.4 to 4.1 MPa).[3] Thus this new concrete has a compressive strength over three times that of presently

available concretes of the same unit weight. Similarly, the flexural strength of this concrete is several times higher than that of equivalent unit weight insulating concretes presently available.

The modulus of elasticity for 50 pcf (800 kg/m^3) cellular or insulating aggregate concrete would be about 300,000 psi (2000 MPa).[3] The calculated modulus of elasticity for the new concrete, using the method in Section 8.5.1 of Ref. 5 with values of 50 pcf (800 kg/m^3) and 1990 psi (13.7 kg/m^3) for the weight and compressive strength, respectively, would be about 520,000 psi (3600 MPa). The average of 3 measured values listed in Table 5 is 933,000 psi (6,400 MPa), or 1.8 times as much as the calculated value.

These strength and weight properties combined with the low shrinkage (discussed later) result in a concrete well suited for use in walls of low rise buildings.

Freezing and Thawing Resistance

Two types of freezing and thawing cycles were used to determine concrete durability. For the first test, 3x3x11-1/4-in. (75x75x285-mm) specimens from Mix No. 3M-CX were subjected to 300 cycles of freezing and thawing in water according to ASTM Designation: C666, Procedure A.[4] Specimens were moist-cured 7 days at 73.4±3°F (23±1.7°C) and 100% RH, air-dried for 20 days at 73.4±3°F (23±1.7°C) and 50±5% RH, and then soaked in water at 73.4±3°F for 24 hours prior to testing.

The ASTM C 666 test provides an extremely severe exposure, even for normal weight, high-strength concrete. Many specifications use a relative dynamic modulus of elasticity value of 80% after 300 cycles as an acceptance criteria. The average relative dynamic modulus of elasticity after 300 cycles for this concrete was 55%. The average relative modulus of elasticity after 200 cycles was 91%. While these results may not be considered acceptable for regular structural concrete, they are considered remarkable for the usual insulating concrete of 50 pcf (800 kg/m^3) unit weight. Typical insulating concrete would have disintegrated well before 200 cycles.

Concrete used in walls is never saturated during freezing. A more realistic freezing and thawing cycle is freezing and thawing in air, with a 1/2 hour water soak before each freezing exposure. Specimens measuring 3x3x11-1/4-in. (75x75x285-mm) from Mix Nos. 3M-A and 3M-B were subjected to this procedure. Specimens were moist-cured for 14 days at 73.4±3°F (23±1.7°C) and 100% RH, and then air-dried for 14 days at 73.4±3°F (23±1.7°C) and 50±5% RH prior to testing. Because only one cycle per day can be done, only 150 cycles were completed at the most recent set of readings. However, at 150 cycles, the average relative dynamic modulus of elasticity for six specimens was 123%. Thus the relative dynamic modulus had increased due to additional curing rather than suffering any damage from the freeze-thaw cycling.

There is every indication from the freeze-thaw tests conducted that this concrete used in building walls will have acceptable durability.

Drying Shrinkage

Drying shrinkage measurements were made on specimens from Mix Nos. 3M-C, 3M-CX, and 3M-CYT. The 3x3x11-1/4-in. (75x75x285-mm) prisms were moist-cured at 73.4±3°F (23±1.7°C) and 100% RH for 7 days, and then air-dried at 73.4±3°F (23±1.7°C) and 50±5% RH. Data are available from specimens which were dried for 161, 179, and 355 days. Drying shrinkage values for these three groups of specimens are 0.088, 0.087 and 0.093%, respectively.

It is useful to compare drying shrinkage obtained on these concretes with that normally expected on other concretes in general use. Shrinkage of structural lightweight aggregate concrete generally is within the range of 0.05 to 0.09%.[6] Shrinkage of insulating concrete, having ovendry unit weight of 50 pcf (800 kg/m^3) or less, can range from 0.10 to 0.60%.[3] An average value for insulating concretes is approximately 0.30%.[3] Thus, the lightweight concrete developed in this program has a shrinkage within the range of that expected for structural lightweight aggregate concrete, and much lower than that expected for commonly used insulating concrete of approximately the same unit weight. Therefore, the shrinkage obtained on this concrete is low for its unit weight and satisfactory for use in building walls.

Thermal Conductivity

Thermal conductivities were determined 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."(4)

Test Specimens: Two specimens from Mix No. 3M-A and two specimens from Mix No. 3M-B were tested. Nominal specimen dimensions were 2x12x12 in. (50x300x300 mm). Specimens were moist-cured at 73.4±3°F (23±1.7°C) and 100% RH for seven days, and then air-dried at 73±5°F (23±3°C) and 45±15% RH for 58 to 70 days. Specimens were oven dried before testing to eliminate effects of moisture migration during testing. Measured specimen dimensions and unit weights are given in Table 6.

Test Procedure: Using a guarded hot plate, two identical samples of the material to be tested are placed on either side of a horizontal flat plate heater assembly consisting of a 5.88-in. (149-mm) square inner (main) heater surrounded by a separately controlled guard heater to form a 12-in. (305-mm) assembly. The function of the guard heater is to eliminate lateral heat flow to or from the main heater thereby forcing all heat generated in the main heater to flow in the direction of the two test samples. Liquid cooled heat sinks are also placed in contact with the samples producing a uniform and constant temperature on the outside of each sample. The apparatus is surrounded by a container filled with expanded

TABLE 6 - MEASURED PROPERTIES OF THERMAL CONDUCTIVITY SPECIMENS

Measured Property	Mix No. 3M-A		Mix No. 3M-B	
	Specimen No. 1	Specimen No. 2	Specimen No. 1	Specimen No. 2
Overall Dimensions, in. (mm)	12.0x12.0 (305x305)	12.0x12.0 (305x305)	12.1x12.0 (306x305)	12.1x12.0 (308x305)
Average Thickness, in. (mm)	2.00 (51)	2.01 (51)	2.05 (52)	2.00 (51)
Ovendry Unit Weight, pcf (kg/m^3)	49.9 (799)	49.6 (794)	48.9 (783)	49.3 (791)

perlite insulation. The perlite insulation serves as a secondary guard. The guarded hot plate apparatus is located in a laboratory maintained at 73.4±3°F (23.0±1.7°C), and 50±5% relative humidity.

The rate of heat flow through the specimens is determined by measuring heat input into the heater plate. Thermal conductivity is calculated from three sets of data collected after equilibrium heat flow and temperatures are reached. Data sets are collected at time intervals of not less than 30 minutes.

Thermal conductivity was calculated using:

$$k = \frac{(Q/A)}{(WT/Wx)} \qquad (1)$$

where:

k = average thermal conductivity of 2 specimens

Q = power dissipation in the main heater

A = the metering surface area taken twice

Wx = total thickness of both test specimens

WT = the total temperature difference across both specimens

Test specimen temperatures are measured by chromel/alumel thermocouples embedded near the specimen surfaces. Thermocouples were placed in grooves previously sawed in specimens. A silicone sealant was used to fill the groove flush with the specimen surface and to secure thermocouples in place. A cement paste with lightweight aggregate fines was used to fill small holes in the specimen surface. For each of the two surfaces of the two specimens, three thermocouples were located

in the region of the main heater, and two were located in the region of the guard heater.

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 7.

Test Results: Table 7 presents thermal conductivity test results for Mix No. 3M-A specimens at four mean temperatures and for Mix No. 3M-B specimens at three mean temperatures. Thermal conductivity test results for concrete from Walls 1 and 2 are given in Reference 2.

Table 7 values are averages for 3 consecutive data readings obtained after steady-state equilibrium was achieved. Test duration is the time lapsed from the first to the third reading. The average temperature gradient is the temperature gradient across each specimen, averaged for the two specimens. Other terms used in Table 7 are defined in ASTM Designation: C1045, "Calculating Thermal Transmission Properties from Steady-State Heat Flux Measurements."[4]

A plot of thermal conductivity versus mean specimen temperature is presented in Fig. 9. Thermal conductivity increases with increasing mean temperature for specimens from Mix Nos. 3M-A and 3M-B.

Thermal conductivities at a specimen mean temperature of 70°F (21°C) were interpolated from measured values. Average thermal conductivities for Mix No. 3M-A and 3M-B, respectively,

TABLE 7 - MEASURED THERMAL CONDUCTIVITIES OF LIGHTWEIGHT CONCRETE SPECIMENS*

Mix No.	Test Date	Test Duration, hrs:min	Hot Plate Temp., °F (°C)	Cold Plate Temp., °F (°C)	ΔT Temperature Differential, °F (°C)	Specimen Mean Temp., °F (°C)	q Heat Flux, Btu/hr•sq ft (W/sq m)	k Thermal Conductivity, Btu•in./hr•sq ft•°F (W/m•K)
3M-A	11/26/85	2:45	44.9 (7.2)	27.0 (-2.8)	18.0 (10.0)	35.9 (2.2)	14.62 (46.12)	1.53** (0.22)
3M-A	11/27/85	3:05	68.2 (20.1)	50.6 (10.4)	17.6 (9.8)	59.4 (15.2)	14.62 (46.12)	1.56** (0.22)
3M-A	12/2/85	1:20	88.0 (31.1)	71.1 (21.7)	16.9 (9.4)	79.5 (26.4)	14.55 (45.91)	1.61** (0.23)
3M-A	12/3/85	3:20	122.0 (50.0)	105.5 (40.9)	16.5 (9.2)	113.7 (45.4)	14.55 (45.91)	1.65** (0.24)
3M-B	12/10/85	3:25	44.2 (6.8)	26.2 (-3.2)	17.9 (10.0)	35.2 (1.8)	14.55 (45.91)	1.54*** (0.22)
3M-B	12/11/85	2:20	86.3 (30.2)	69.4 (20.8)	16.9 (9.4)	77.8 (25.4)	14.55 (45.91)	1.63*** (0.24)
3M-B	12/12/85	2:35	120.7 (49.3)	104.5 (40.3)	16.4 (9.1)	112.6 (44.9)	14.55 (45.91)	1.69*** (0.24)

* Measured in accordance with ASTM Designation: C177 using a guarded hot plate. Specimens were ovendried before testing.
** Average effective thickness of specimens (distance between thermocouples) was 1.87 in. (47.5 mm).
*** Average effective thickness of specimens (distance between thermocouples) was 1.90 in. (48.3 mm).

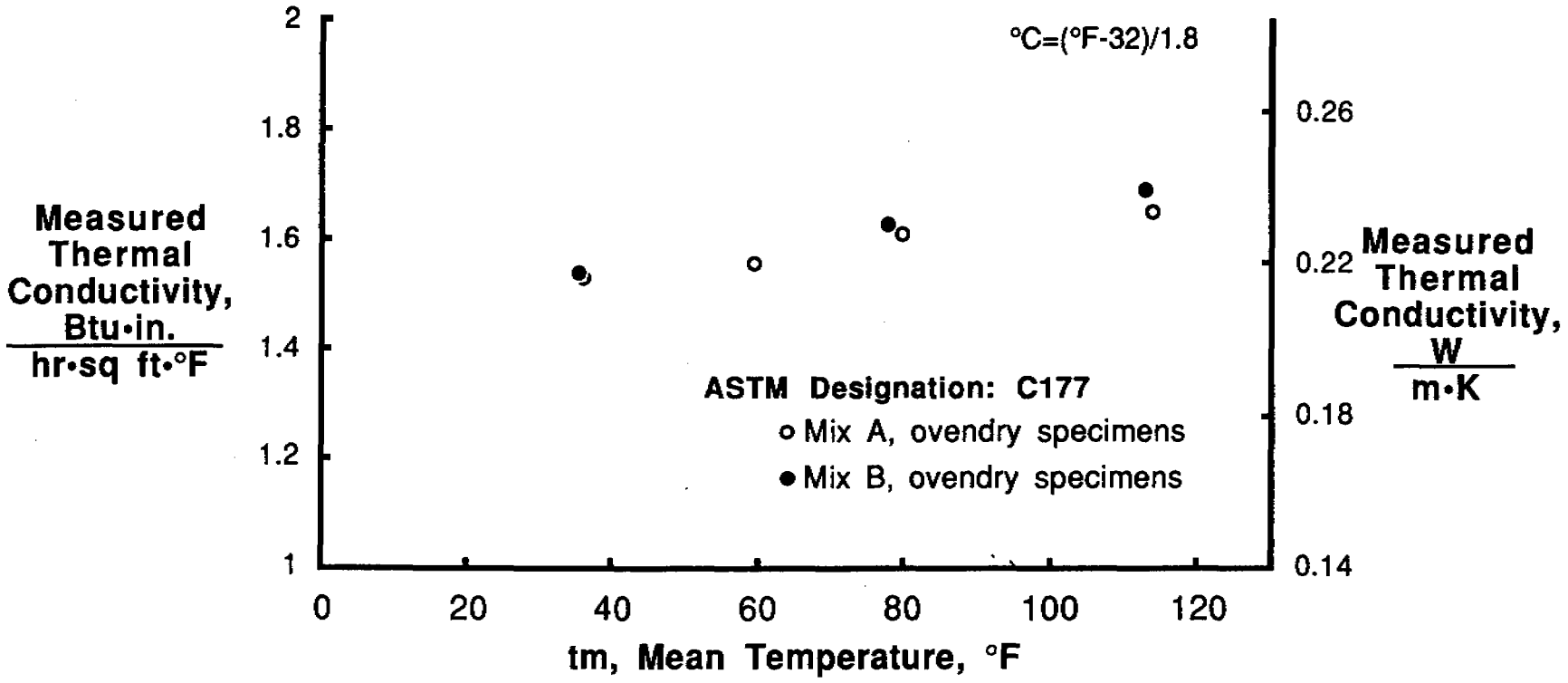


Fig. 9 Measured Thermal Conductivity of Lightweight Concrete Specimens

were 1.59 and 1.61 Btu•in./hr•ft^2•°F (0.23 and 0.23 W/m•K) at a specimen mean temperature of 70°F (21°C).

Average thermal conductivity of ovendry normal weight concrete specimens with embedded thermocouples was measured according to ASTM Designation: C177 for a previous study. Measured thermal conductivity was 16.1 Btu•in./hr•ft^2•°F (2.32 W/m•K) at a specimen mean temperature of 70°F (21°C).[8] Average measured thermal conductivity of the lightweight concrete developed for this project is 1/10th that for normal weight concrete.

Specific Heat

Specific heat is a measure of thermal storage capacity. Specific heats of Concrete Mix Nos. 3M-A and 3M-B were measured using a method similar to U.S. Army Corps of Engineers Specification CRD-C124-73, "Method of Test for Specific Heat of Aggregates, Concrete, and Other Materials (Method of Mixtures)".[9]

Test Specimens: Specific heat samples, shown in Fig. 10, were selected from crushed parts of two 3x6-in. (75x150-mm) cylinders moist-cured at 73.4±3°F (23±1.7°C) and 100% R.H. until tested. Tests were performed on samples from Mix Nos. 3M-A and 3M-B, respectively, 35 and 33 days after casting. Samples were taken from the portion of each crushed cylinder that passes through a 1 in. (25-mm) sieve and is retained on a No. 4 sieve (4.75 mm). After the samples were crushed and sieved they were immersed in room temperature water for 3 to 4

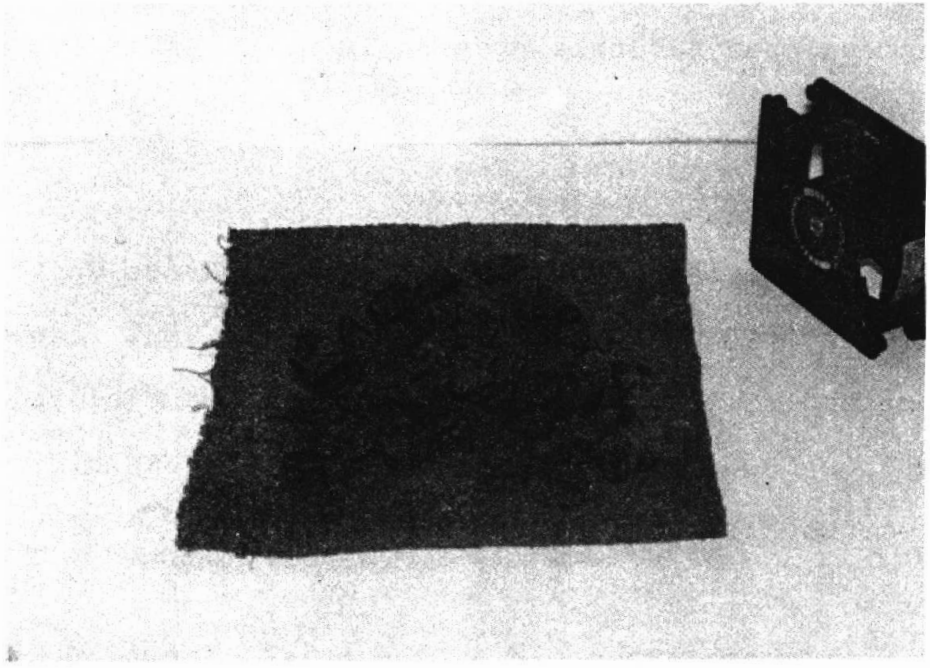


Fig. 10 Specific Heat Test Samples

days. Just prior to testing each sample was brought to a saturated surface dry condition.

Test Procedure: To determine specific heat, a sample is heated in a warm bath at 115±1°F (46.1±0.6°C) and then transferred to a calorimeter containing room-temperature water. After the water in the calorimeter reaches a constant temperature the specimen is removed. At this time the sample is cooled in water at 35±1°F (1.7±0.6°C) and again transferred to the calorimeter. Specific heat is calculated from the sample temperature history and the sample mass. The cycle is repeated two more times or until consistent data are obtained. Reported results are average of results from three cycles.

To calculate specific heat of the material in a dry state, weights of the material in the particular dry state and the saturated surface dry (SSD)* state are used. Whiting, Litvin and Goodwin[10] used the following equation to calculate specific heat of concrete for different moisture conditions:

$$c = \frac{c_{SSD} + \gamma(y-1)}{1 + \gamma(y-1)} \qquad (2)$$

where:

c = specific heat of samples at any moisture content

c_{SSD} = specific heat of saturated surface dry samples

y = moisture content expressed as a fraction of the SSD moisture content

γ = SSD moisture content

$$\gamma = \frac{W_{SSD} - W_{OD}}{W_{SSD}} \qquad (3)$$

*An SSD material is a saturated material with surface water removed.

where:

W_{SSD} = SSD weight of sample

W_{OD} = ovendry weight of sample

After testing, specific heat samples were oven dried so that SSD moisture contents could be determined.

Test Results: Specific heat values obtained in this investigation are given in Table 8. Values are for concrete in saturated surface dry, air dry, and ovendry conditions. Specific heats in the air dry and ovendry conditions were calculated using Eqs. (2) and (3). The SSD moisture contents were determined from crushed specific heat samples that were oven dried after test.

Air dry and ovendry unit weights presented in Table 8 were determined from previously described thermal conductivity test specimens. These specimens were moist-cured at 73.4±3°F (23±1.7°C) and 100% RH for seven days, air-dried at 73±5°F (23±3°C) and 45±15% RH for 58 to 70 days, and then oven dried.

Specific heat values for saturated surface dry, air dry and ovendry conditions vary due to differences in moisture content. Since the specific heat of water is 1.0 Btu/lb•°F (4187 J/kg•K), concrete at a higher moisture content has a higher value of specific heat.

Table 8 also lists previously determined values of specific heat for perlite concrete and normal weight concrete. The specific heat of ovendry perlite concrete is similar to that for concrete from Mix Nos. 3M-A and 3M-B. The specific heats for air dry and SSD perlite concrete specimens are greater than

TABLE 8 - SPECIFIC HEAT OF LIGHTWEIGHT STRUCTURAL CONCRETE

Mix No.	Saturated Surface Dry (SSD)			Air Dry*			Ovendry	
	Unit Weight, pcf_3 (kg/m^3)	Moisture Content, % ovendry Weight	Specific Heat, Btu/lb·°F (J/kg·K)	Unit Weight, pcf_3 (kg/m^3)	Moisture Content, % ovendry Weight	Specific Heat, Btu/lb·°F (J/kg·K)	Unit Weight, pcf_3 (kg/m^3)	Specific Heat, Btu/lb·°F (J/kg·K)
3M-A	55 (880)	20	0.261 (1090)	47 (750)	1.3	0.123 (520)	46 (740)	0.113 (470)
3M-B	57 (910)	22	0.243 (1020)	47 (750)	1.9	0.095 (400)	46 (740)	0.078 (330)
Previous Perlite Concrete Test[11]**	68 (1090)	62	0.444 (1860)	46 (740)	9.5	0.179 (750)	42 (670)	0.100 (420)
Previous Normal Weight Concrete Test[8]***	148 (2370)	4.8	0.214 (900)	144 (2300)	2.1	0.193 (810)	141 (2260)	0.175 (730)

*Air dry moisture is the moisture content of a specimen in equilibrium with its surrounding air. Air dry moisture contents of specimens from Mix Nos. 3M-A and 3M-B were determined from thermal conductivity specimens moist-cured at 73.4±3°F (23±1.7°C) and 100% RH for seven days, and then air-dried at 73±5 °F (23±3 °C) and 45+15% RH for 58 to 70 days.

**Expanded perlite aggregate

***Sand and gravel aggregate

for concrete from Mix Nos. 3M-A and 3M-B because the perlite concrete specimens have significantly greater moisture contents.

The specific heats of the ovendry and air dry concrete from Mix Nos. 3M-A and 3M-B are less than those for normal weight concrete because of the high density of the normal weight concrete. The specific heats of the SSD concrete from Mix Nos. 3M-A and 3M-B are greater than that of the normal weight concrete because concrete from Mix Nos. 3M-A and 3M-B have significantly greater SSD moisture contents than the normal weight concrete.

Thermal Diffusivity

Thermal diffusivity is a physical property of a material that defines the time rate of change of temperature at any point within a body. In heat transfer applications, thermal diffusivity defines the rate of heating of a thermal storage mass.

Values of thermal diffusivity for concrete from Mix Nos. 3M-A and 3M-B were calculated, using basic heat transfer equations, and measured.

Calculated Values: Theoretically, thermal diffusivity is equal to the thermal conductivity divided by the heat capacity per unit volume and may be used as an index of the facility with which the material will undergo temperature change. A calculated value of the thermal diffusivity of a sample can be obtained from the following equation:

$$\alpha = \frac{k}{\rho . c} \qquad (4)$$

where:

α = thermal diffusivity, ft^2/hr (m^2/s)

k = thermal conductivity, Btu/hr•ft•°F (W/m•K)

ρ = unit weight, pcf (kg/m^3)

c = specific heat, Btu/lb•°F (J/kg•K)

Table 9 lists values of thermal diffusivity calculated for samples from concrete Mix Nos. 3M-A and 3M-B. These calculations were performed using ovendry values for unit weight, specific heat, and thermal conductivity. Thermal conductivity was measured with a guarded hot plate. An interpolated value for a mean specimen temperature of 70°F (21°C) was used.

Test Procedures and Samples: Thermal diffusivity of samples from Mix Nos. 3M-A and 3M-B were measured using a method similar to U.S. Army Corps of Engineers Specification CRD-C36-73, "Method of Test for Thermal Diffusivity of Concrete."[9] Tests were performed on 6x12-in. (150x300 mm) test cylinders with a Type T thermocouple placed at the center of each specimen during casting. Specimens were cured at 73.4±3°F (23±1.7°C) and 100% R.H. until testing. Specimens from Mix Nos. 3M-A and 3M-B, respectively, were tested 30 days and 36 days after casting.

To determine thermal diffusivity a specimen is immersed in boiling water until the center reaches 200°F (93°C). The specimen is then transferred to a cold water bath maintained at 40±3°F (4.4±1.7°C), as shown in Fig. 11. The cooling history

TABLE 9 - CALCULATED THERMAL DIFFUSIVITY OF LIGHTWEIGHT STRUCTURAL CONCRETE

Mix No.	ρ Ovendry Unit Weight, pcf (kg/m^3)	c Ovendry Specific Heat, Btu/lb°•F (J/kg•K)	k Ovendry Thermal Conductivity, Btu/hr•ft•°F (W/m•K)	α Calculated Thermal Diffusivity, ft^2/hr (m^2/hr)
3M-A	46 (740)	0.113 (470)	0.133 (0.23)	0.026 (0.0024)
3M-B	46 (740)	0.078 (330)	0.134 (0.23)	0.037 (0.0034)
Previous Perlite Concrete Test[11]*	42 (670)	0.100 (420)	0.120 (0.21)	0.029 (0.0027)
Previous Normal Weight Concrete Test[8]**	141 (2260)	0.175 (730)	1.34 (2.32)	0.054 (0.0050)

* Expanded perlite aggregate
** Sand and gravel aggregate

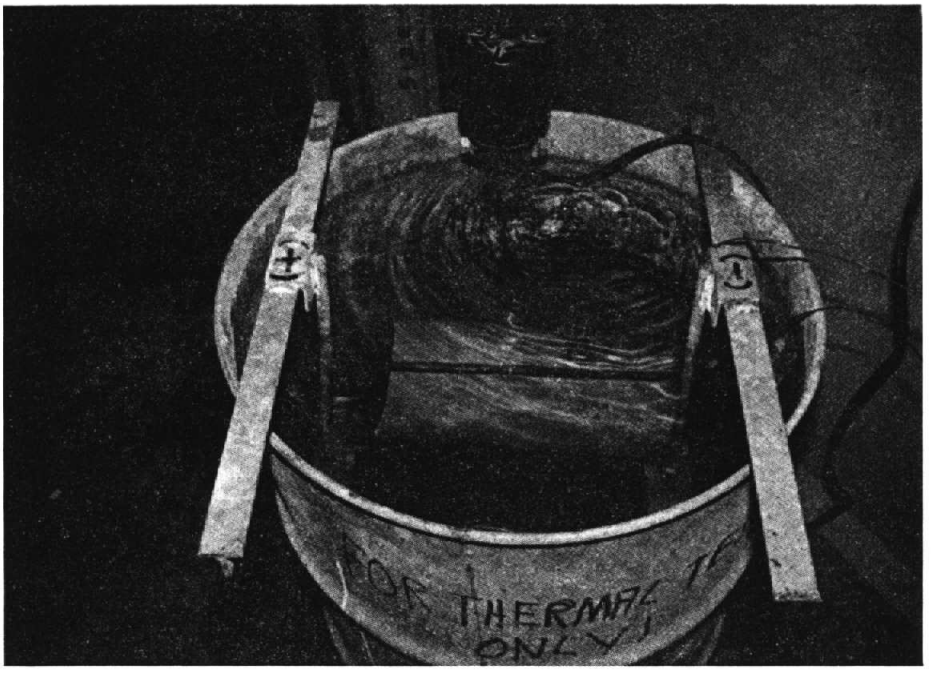


Fig. 11 Specimen Immersed in Cold Bath During Thermal Diffusivity Test

of the specimen is monitored until the difference between the center of the specimen and the water is 8°F (4°C).

To calculate the measured diffusivity the temperature difference between the cold bath and the specimen center is determined. The time elapsed between the temperature difference of 80°F (26.7°C) and 20°F (-6.7°C) is inserted in the equation below:

$$\alpha = 0.812/(t_1-t_2) \qquad \text{IP Units} \qquad (5)$$

$$\alpha = 0.0419/(t_1-t_2) \qquad \text{SI Units}$$

where:

α = thermal diffusivity, ft^2/hr (m^2/hr)

t_1-t_2 = elapsed time between temperature differences of 80°F (26.7°C) and 20°F (-6.7°C), minutes

Test Results: Measured values of thermal diffusivity are shown in Table 10. Two tests were performed on each specimen.

Thermal diffusivities from Table 10 cannot be directly compared to values from Table 9 because Table 9 is calculated values from tests on ovendry specimens and Table 10 presents measured values from tests on saturated specimens.

Tables 9 and 10 list previously determined values of thermal diffusivity for saturated perlite concrete and saturated normal weight concrete. Calculated thermal diffusivity of the perlite concrete is similar to that for lightweight concrete specimens from Mix Nos. 3M-A and 3M-B. Calculated and measured thermal diffusivities of normal weight concrete are significantly greater than those for the perlite

TABLE 10 - MEASURED THERMAL DIFFUSIVITY OF SATURATED LIGHTWEIGHT STRUCTURAL CONCRETE

Mix No.	Test No.	Unit Weight Before Testing, pcf (kg/m^3)	t_1-t_2, min	Avg. Measured Thermal Diffusivity, ft^2/hr (m^2/hr)
3M-A	1	*	81	0.0100† (0.00092)
	2	54 (860)	82	
3M-B	1	54 (860)	75	0.0108† (0.00100)
	2	54 (860)	76	
Previous Saturated Perlite Concrete Test(11)**	1	65 (1040)	95	0.0085† (0.00079)
	2	66 (1060)	96	
Previous Saturated Normal Weight Concrete Test(8)***	1	151 (2420)	22	0.0369† (0.00343)
	2	151 (2420)	22	

* Not available
** Expanded perlite aggregate
*** Sand and gravel aggregate
† Values for Test Nos. 1 and 2 were within 0.0001 ft^2/hr (0.00002 m^2/hr).

concrete and lightweight concrete specimens from Mix Nos. 3M-A and 3M-B.

Thermal Expansion

Thermal expansion of concrete from Mix Nos. 3M-A and 3M-B was measured at CTL. Tests were performed in general compliance with ASTM Designation: E228-79, "Standard Test Method for Linear Expansion of Rigid Solids with a Vitreous Silica Dilatometer."[4]

Test Specimens: Thermal expansion tests were performed on 20 specimens, 10 from concrete of Mix No. 3M-A and 10 from concrete of Mix No. 3M-B. After casting, one 6x12-in. (150x300-mm) cylinder from each mix was moist-cured at 73.4±3°F (23±1.7°C) and 100% RH for seven days, and then cured at 73±5°F (23±3°C) and 45±15% RH for 42 to 46 days. Air-dried cylinders had unit weights of 49 pcf (780 pcf) each. Using a 1/2-in. (13-mm) diameter diamond-tipped core drill bit, specimens were cored from the 6x12-in. (150x300-mm) cylinders. Ends of cores were cut with a precision saw to obtain an overall length of approximately 3 in. (75 mm). Core ends were lapped to provide nominal 0.5-in. (13-mm) diameter by 3-in. (75-mm) long cylindrical dilatometer specimens, as shown in Fig. 12.

Before testing, dilatometer specimens were ovendried at 212°F (100°C) for at least 24 hours to remove free moisture.

Thermal expansion was measured on ten specimens of each concrete type to reduce the effects a single piece of aggregate may have on results for one test on a 1/2-in. (13-mm) diameter core.

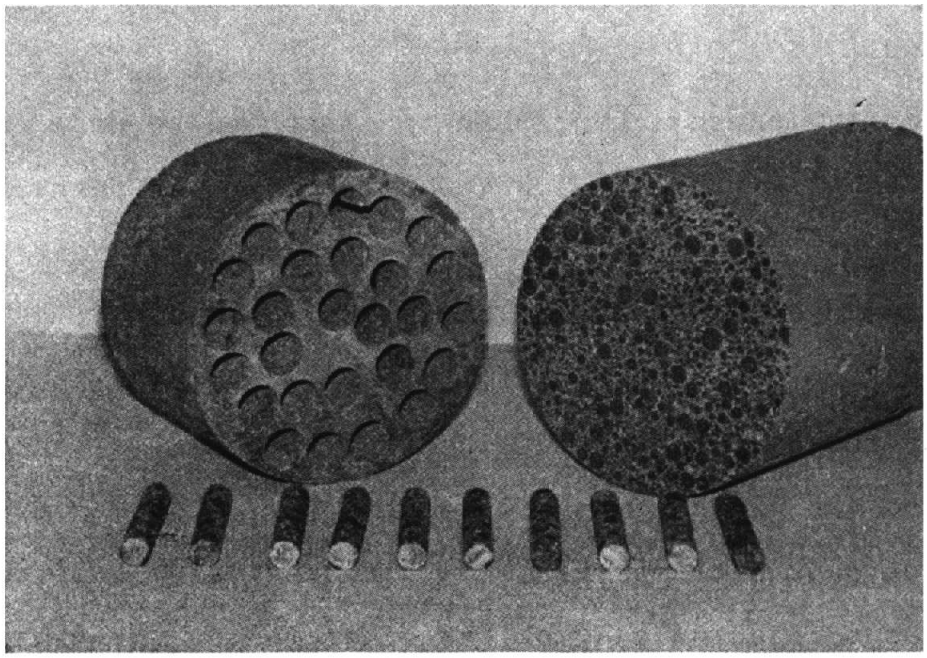


Fig. 12 Thermal Expansion Test Samples

Test Procedure: The apparatus used for determination of thermal expansion consists of three components: a dilatometer, an environmental chamber, and an X-Y recorder.

The dilatometer consists of instruments for measuring expansion of the heated or cooled specimens. During testing the specimen was located at the closed end of a fused silica tube inserted into an environmental chamber, as shown in Fig. 13. The open end of the tube was rigidly fixed to a support base.

Thermally-induced changes in specimen length were transmitted by a fused silica rod attached to an Invar bar that rode on smooth pulleys. The end of the Invar bar rested against the plunger of a dial gage with a 0.0001-in. (0.0025-mm) calibrated sensitivity. Pressure from the light spring of the dial gage maintained the specimen in contact with the closed end of the fused silica tube.

The core of a linear variable differential transformer (LVDT) was mounted axially on the outer end of the dial gage plunger. Dial gage and LVDT housings were mounted on the base support. Movement of the specimen was monitored by the LVDT. Changes in length for each test were corrected for expansion of the test system itself. Correction factors were calculated by running thermal expansion tests on 3-in. (75-mm) fused quartz samples.

An X-Y plotter was used to continuously record thermal expansion of specimens as measured by the LVDT, and temperature as measured by the second thermocouple shown in Fig. 13.

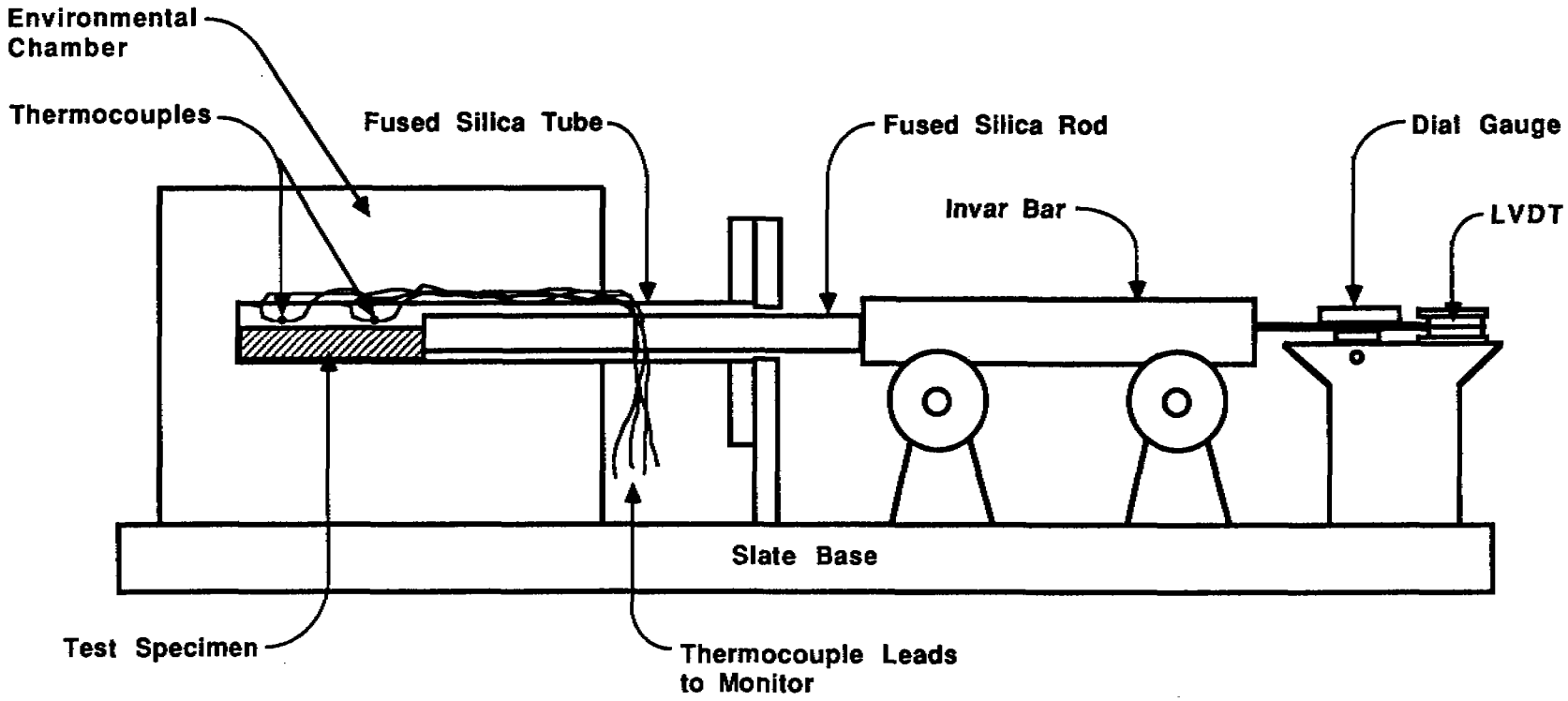


Fig. 13 Longitudinal Cross Section of Dilatometer

During each test, a specimen was positioned in the fused silica tube of the dilatometer and the fused silica rod was seated against the end of the specimen. The specimen temperature was decreased from room temperature to approximately 0°F (-18°C) with the environmental chamber. The temperature was then increased to approximately 350°F (175°C). After reaching 350°F (175°C), the specimen was cooled to room temperature. Heating and cooling rates ranged from 3 to 10°F/minute (2 to 6°C/minute). Temperature and thermal expansion were recorded continuously on the X-Y plotter.

Reference 12 presents data on thermal lag of the internal temperature of a normal weight concrete specimen compared to the externally applied temperature for similar thermal expansion tests. Based on Reference 12 data, the coefficient of thermal expansion test results for this program are not significantly affected by thermal lag.

Test Results: The coefficient of thermal expansion for each test is presented in Tables 11 and 12, respectively, for concrete from Mix Nos. 3M-A and 3M-B. The tables also list the original specimen length (ℓ_o), the test temperature range (ΔT), the change in specimen length for the specified temperature range ($\Delta\ell$), and the strain ($\Delta\ell/\ell_o$). The coefficient of thermal expansion is equal to the strain divided by the associated temperature range. Values listed are for heating the specimen from approximately 0°F (-18°C) to approximately 350°F (175°C).

The mean and standard deviation of the coefficient of thermal expansion are presented at bottom of each table.

TABLE 11 - COEFFICIENT OF THERMAL EXPANSION FOR CONCRETE FROM MIX NO. 3M-A

Specimen No.	Original Length lo, in. (mm)	Temperature Range ΔT, °F (°C)	Length Change Δl, in. (mm)	Strain Δl/lo, in./in. or mm/mm in thousandths	Coefficient of Thermal Expansion,* in./in. per °F (mm/mm per °C) in millionths
1	3.0360 (77.114)	364 (202)	0.0047 (0.119)	1.55	4.3 (7.7)
2	3.0320 (77.013)	354 (197)	0.0047 (0.119)	1.55	4.4 (7.9)
3	3.0590 (77.699)	365 (203)	0.0044 (0.112)	1.44	3.9 (7.1)
4	3.0525 (77.534)	359 (199)	0.0045 (0.114)	1.47	4.1 (7.4)
5	3.0450 (77.343)	361 (201)	0.0046 (0.117)	1.51	4.2 (7.5)
6	3.0310 (76.987)	364 (202)	0.0041 (0.104)	1.35	3.7 (6.7)
7	3.0800 (78.232)	353 (196)	0.0039 (0.099)	1.27	3.6 (6.5)
8	3.0298 (76.957)	361 (201)	0.0032 (0.081)	1.06	2.9 (5.3)
9	3.0355 (77.102)	353 (196)	0.0032 (0.081)	1.05	3.0 (5.4)
10	3.0480 (77.419)	350 (194)	0.0033 (0.084)	1.08	3.1 (5.6)
Mean	-	-	-	-	3.7 (6.7)
Standard Deviation	-	-	-	-	0.5

*Specimens were oven dried before testing.

TABLE 12 - COEFFICIENT OF THERMAL EXPANSION FOR CONCRETE FROM MIX NO. 3M-B

Specimen No.	Original Length lo, in. (mm)	Temperature Range ΔT, °F (°C)	Length Change Δl, in. (mm)	Strain Δl/lo, in./in. or mm/mm in thousandths	Coefficient of Thermal Expansion,* in./in. per °F (mm/mm per °C) in millionths
1	3.0290 (76.937)	359 (199)	0.0041 (0.104)	1.35	3.8 (6.8)
2	3.0300 (76.962)	354 (197)	0.0034 (0.086)	1.12	3.2 (5.7)
3	3.0400 (77.216)	357 (198)	0.0033 (0.084)	1.08	3.0 (5.5)
4	3.0330 (77.038)	358 (199)	0.0035 (0.089)	1.15	3.2 (5.8)
5	3.0310 (76.987)	359 (199)	0.0038 (0.097)	1.25	3.5 (6.3)
6	3.0330 (77.038)	354 (197)	0.0041 (0.104)	1.35	3.8 (6.9)
7	3.0440 (77.318)	368 (204)	0.0031 (0.079)	1.02	2.8 (5.0)
8	3.0110 (76.479)	354 (197)	0.0041 (0.104)	1.36	3.8 (6.9)
9	2.9800 (75.692)	356 (198)	0.0036 (0.091)	1.21	3.4 (6.1)
10	2.7960 (71.018)	363 (202)	0.0031 (0.079)	1.11	3.1 (5.5)
Mean	–	–	–	–	3.4 (6.1)
Standard Deviation	–	–	–	–	0.4

*Specimens were oven dried before testing.

Table 13 summarizes test results and lists previously determined thermal expansion values for lightweight and normal weight concrete. Coefficients of thermal expansion for concrete from Mix Nos. 3M-A and 3M-B are less than those for other lightweight and normal weight concrete.

Casting of Full Size Wall Panels

A complete description of the full-size panels cast for the heat transfer measurements will be given in a later report.[2] However, it is desirable in this report to discuss the method of casting and consolidation of the concrete in the wall panel forms.

Because of its low unit weight, this concrete does not consolidate as readily as heavier concrete. Consolidation of specimens by rodding is insufficient as the rod merely leaves holes in the concrete without consolidating it. Internal vibration is not very effective with small castings. Internal vibration may be more effective with larger castings, such as vertically cast-in-place walls, because of the added weight of material in the form to help consolidation. Castings to determine the effectiveness of this procedure were not made.

All laboratory test specimens (cylinders, prisms, etc.) were consolidated on a vibrating table as shown in Fig. 14. This did a satisfactory job. However, a surcharge weight used to apply downward pressure to the concrete would have speeded consolidation.

TABLE 13 - COEFFICIENTS OF THERMAL EXPANSION FOR NORMAL WEIGHT AND LIGHTWEIGHT CONCRETE

Concrete Type	Temperature Range, °F (°C)	Coefficient of Thermal Expansion, in./in. per °F (mm/mm per °C) in millionths	Reference No.
Lightweight Structural Concrete			
Various	*	3.9 to 6.1 (7 to 11)	13
Mix Nos. 3M-A & 3M-B	0 to 350 (-18 to 175)	3.4 to 3.7 (6.1 to 6.7)	--
Normal Weight Concrete			
with Quartz Aggregate	*	6.6 (11.9)	13
with Sandstone Aggregate	*	6.5 (11.7)	13
with Gravel Aggregate	*	6.0 (10.8)	13
with Gravel Aggregate	81 to 1600 (27 to 871)	7.0 (12.6)	12
with Dolomite Aggregate	81 to 1600 (27 to 871)	6.2 (11.2)	12
with Granite Aggregate	*	5.3 (9.5)	13
with Basalt Aggregate	*	4.8 (8.6)	13
with Limestone Aggregate	*	3.8 (6.8)	13

*Not Available.

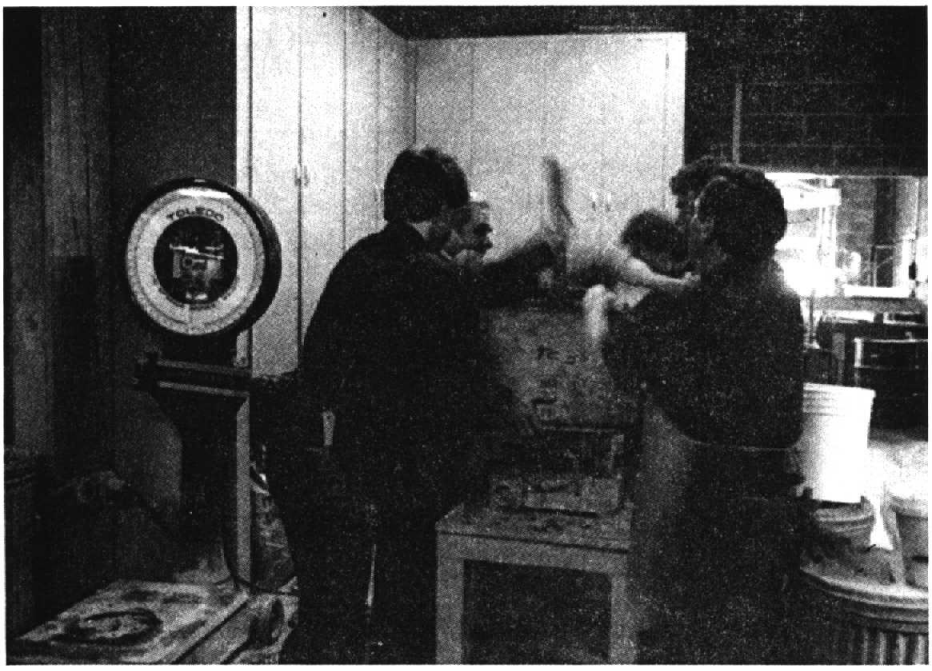


Fig. 14 Consolidation of Test Specimens Using a Vibrating Table

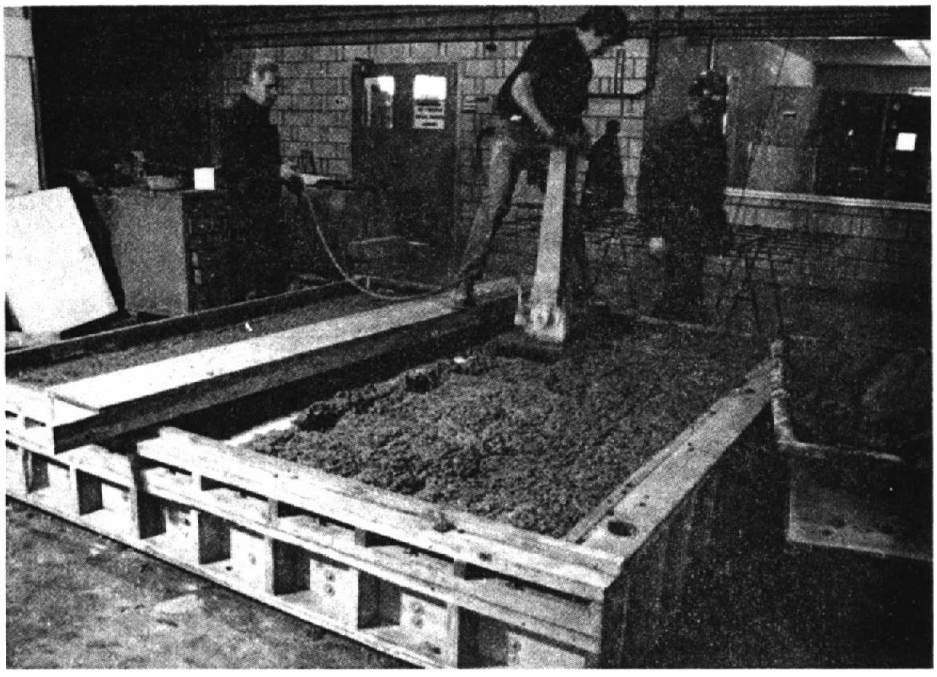


Fig. 15 Consolidation of Wall Panel Using a Plate Vibrator

Many insulating concretes are supplied in a fairly fluid consistency. This makes transporting, placing, consolidation, and finishing very easy. Such concretes use no aggregate or only very fine aggregate, very high air contents, and high water contents. These concretes have low strength and high drying shrinkage. If the test concrete was made to such high fluidity, the aggregate would float (segregate), shrinkage would be high and strength would be low. The concrete would not meet the requirements of this program.

The test wall panels required about 50 cu ft (1.4 m^3) of concrete per panel. Concrete was mixed in a 6 cu ft (0.17 m^3) pan mixer. Ten 5-1/2 cu ft (0.16 m^3) batches were made for each panel. The concrete was transported, as each batch was made, to the form location and shovelled into the horizontal form, filling the form to half its thickness.

Consolidation was accomplished by means of a plate vibrator as shown in Fig. 15. Plate vibrators are frequently used to consolidate stiff consistency concrete in horizontal forms at precast concrete plants. This equipment performed well in consolidating this concrete. No honeycombing was observed when panels were removed from forms.

After filling the form to half thickness, a layer of wire mesh reinforcement was placed on the concrete, the form was then filled, and the concrete consolidated, struck off, floated, and trowelled. When trowelling the concrete, the larger aggregate rather than the cement paste tended to float to the top of the concrete. This made trowelling a little more

difficult than trowelling traditional concretes. The finished surface was flat but bumpy due to the slight protrusions of the lightweight aggregate.

No significant problems were experienced in casting the panels, and it can be concluded that this concrete is satisfactory for use in horizontally precast concrete wall panels.

POLYMER CONCRETE

General

An objective of this investigation is to produce a concrete having a thermal conductivity of 1.0 Btu•in./hr•ft^2•°F (0.14 W/m•K) or less and compressive strength of 3000 psi (21 MPa) or more to act as a thermal break material. It is probably unreasonable to expect to obtain a portland cement concrete with these properties. It is more likely that concrete with such properties might be obtained using a polymer as the cementing medium.

A simplified mix design approach was to use a mix similar to that developed for the portland cement concrete, except to replace the cement, silica fume, water, and entrained air with polymer. Thus the aggregate volume per unit volume of concrete would be the same as the portland cement concrete.

Polymers

Seven different polymer materials were used in this investigation, and these are representative of the type of polymers generally used for polymer concrete.

Methyl Methacrylate Monomer

This material has a water thin consistency and proved to be completely unsuitable for this application. It is more suitable for use in polymer impregnation of portland cement concrete.

Polyester Resin

This is a modified polyester resin supplied by Dow Chemical Company for application in polymer concrete. The resin required thickening (with santicel) and was successful in producing workable mixes from which specimens were cast and tested.

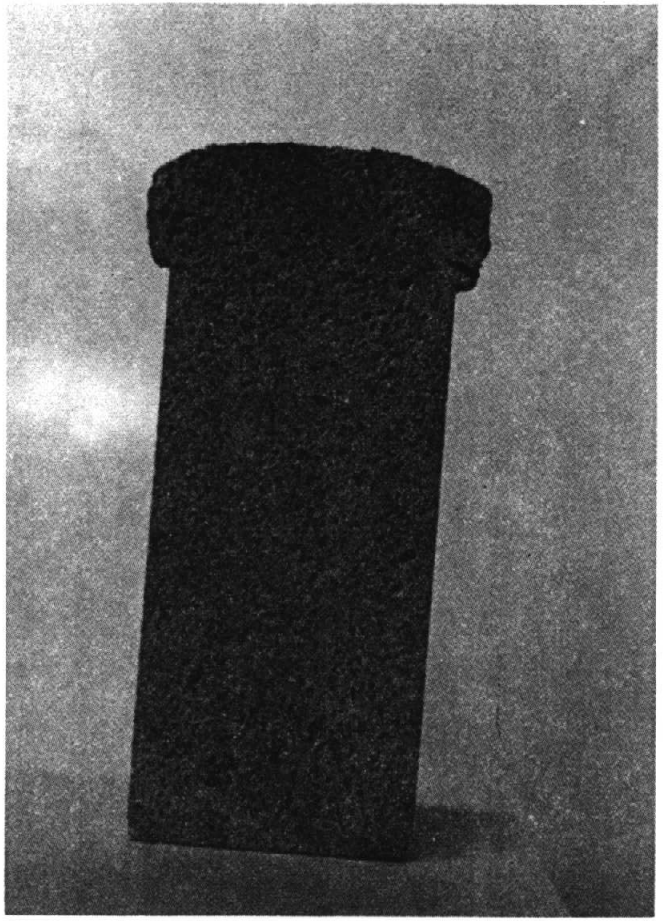
Epoxy Resin

Several epoxy resins were obtained and used in making specimens. All required thickening to obtain suitable concrete consistency. Three epoxies, Concressive 1470, Concressive 1001 LPL, and Concressive AEX 1539G were supplied by Adhesive Engineering Co. Probond 811C and 821C were furnished by Protex Industries, Inc.

Aggregates

All mixes utilized either the 3M Macrolite aggregate with Fillite, combinations of the 3M and PQ aggregates, or the PQ aggregate alone. The PQ aggregates were used in an attempt to lower concrete unit weight, as they have a lower specific gravity than the 3M aggregate. However, epoxy concrete mixes using the PQ aggregate expanded out of the mold before they hardened, as shown in Fig. 16(a). It is probable that heat generated during curing of the epoxy expanded air in the

a) Concrete in Cylinder Mold



b) Cross-Section of Expanded Concrete

Fig. 16 Polymer Concrete with Epoxy Resins and PQ Aggregate Expands Before Hardening

aggregate forcing it out of the aggregate into the body of the mix. A cross-section of the hardened concrete (Fig. 16(b)) showed a very porous structure.

Fillite was utilized as a relatively lightweight material to replace some of the missing fine sizes occurring in mixes using 3M Macrolite aggregate.

Polymer Concrete Properties

Sixteen polymer concrete mixes were made and small cylindrical specimens were cast for unit weight and compressive strength determinations. Because polymers are not water soluble, clean-up of mixers and tools requires the use of solvents such as methylene chloride and methyl ethyl ketone. To avoid some of these difficulties, batches were small and mixing was done manually in throw-away cardboard buckets. Specimens were cast in disposable 3x6-in. (75x150-mm) or 4x8-in. (100x200-mm) molds. Specimens were normally removed from the molds, weighed, and tested in compression 3 days after casting.

Table 14 is a complete list of polymer concrete mixes, unit weights, compressive strengths, and strength-to-weight ratios.

Of all the individual specimens tested, unit weight varied from a low of 46 pcf (736 kg/m^3) to a high of 56 pcf (896 kg/m^3). Compressive strength varied from 1175 to 3020 psi (8.1 to 20.8 MPa).

The best combination of weight and strength was obtained from polymer concrete Mix No. A-5 using Concressive 1539G epoxy resin with the 3M Macrolite aggregate. Values obtained for

TABLE 14 - POLYMER CONCRETE MIXES AND PROPERTIES

Mix No.	Materials				Properties		
	Resin Identification	Resin Type	Aggregates	Thickened with Santicel	Unit Weight, pcf (kg/m^3)	Compressive Strength, psi (MPa)	Strength-to-Weight Ratio, psi/pcf (kPa/(kg/m^3))
-	Project Objective	—	—	—	36 (575)	3000 (21)	83.3 (36.5)
D-1	XUS40047	Polyester	3M, Fillite	No	—	1175 (8.1)	--
D-2	XUS40047	Polyester	3M, Fillite	Yes	55.0 (880)	1980 (13.6)	36.0 (17.7)
D-3	XUS40047	Polyester	3M, Fillite	Yes	54.0 (864)	2720 (13.6)	41.1 (15.4)
A-1	Concressive 1470	Epoxy	3M, Fillite	No	—	300 (2.1)	--
A-2	Concressive 2010-2020	Methyl Methacrylate	3M, Fillite	No	—	--	--
A-3	Concressive 1001 LPL	Epoxy	3M, Fillite	Yes	56.0 (896)	2770 (19.1)	49.5 (21.3)
A-4	Concressive 1539G	Epoxy	3M, Fillite	Yes	54.0 (864)	2820 (19.4)	52.2 (22.5)
A-5	Concressive 1539G	Epoxy	3M, Fillite	Yes	49.6 (794)	3020 (20.8) 2870 (19.8)	60.9 (26.2) 57.9 (24.9)
A-6*	Concressive 1539G	Epoxy	3M, Fillite	Yes	—	—	—
A-7	Concressive 1539G	Epoxy	3M, Fillite, PQ	Yes	46.4 (742)	2360 (16.3)	50.9 (22.0)
A-8	Concressive 1539G	Epoxy	3M, Fillite, PQ	Yes	46.0 (736)	2150 (14.8)	46.7 (20.1)
A-9**	Concressive 1539G	Epoxy	PQ, Fillite	No	35.6 (570)	—	--
P-1	P811C	Epoxy	3M, Fillite	Yes	50.0 (800) 51.6 (826)	1500 (10.3) 1810 (12.5)	30.0 (12.9) 35.1 (15.1)
P-2	P811C	Epoxy	3M, Fillite	Yes	49.0 (784)	1940 (13.4)	39.6 (17.1)
P-3	P811C	Epoxy	3M, Fillite, PQ	Yes	48.0 (768)	1730 (11.9)	36.0 (15.5)
P-4**	P811C	Epoxy	PQ, Fillite	Yes	—	—	—

*Same as Mix A-5. Made specimens for guarded hot plate tests.
**Expanded out of mold.

this mix were a unit weight of 49.6 pcf (794 kg/m^3) and a compressive strength of 3020 psi (20.8 MPa). Proportions for this mix are shown in Table 15.

Thermal conductivity of two specimens from Mix No. A-6 were measured using a guarded hot plate. Specimen dimensions were 1.08x12.32x12.34 in. (27x313x313 mm) and 1.12x12.33x12.33 in. (28x313x313 mm). Measured unit weights were 52.2 and 46.9 pcf (835 and 750 kg/m^3), respectively.

Thermal conductivity test results for three mean temperatures are presented in Table 16. Figure 17 shows thermal conductivity versus specimen mean temperature. Tests were conducted in the same manner as those for the portland cement concrete. Although unit weights for the portland cement concrete and polymer concrete were similar, approximately 50 pcf (800 kg/m^3), the polymer concrete thermal conductivity was about 12% less than that for portland cement concrete.

The unit weight and thermal conductivity of Mix A-6 are not low enough to meet the project objective. The only other available aggregate that could result in lower unit weight concrete was the PQ aggregate. However, as previously stated, mixes made with this aggregate expanded in the mold, resulting in very low strength concrete. An alternative procedure may be to add more aggregate per unit volume of concrete. This may, however, reduce compressive strength below 3000 psi (21 MPa). Additional work is needed to determine whether it is possible to meet the objective polymer concrete requirements.

TABLE 15 - MOST DESIRABLE POLYMER CONCRETE MIX

Material	lb (kg) per cu yd (0.765 m^3) of concrete
Concressive 1539G-epoxy	501 (228)
3M Macrolite, coarse	308 (140)
3M Macrolite, fine	462 (210)
Fillite	71 (32)

TABLE 16 - MEASURED THERMAL CONDUCTIVITIES OF POLYMER CONCRETE SPECIMENS*

Mix No.	Test Date **	Test Duration, hrs:min	Hot Plate Temp., °F (°C)	Cold Plate Temp., °F (°C)	ΔT Temperature Differential, °F (°C)	Specimen Mean Temp., °F (°C)	q Heat Flux, Btu/hr•sq ft (W/sq m)	k Thermal Conductivity, Btu•in./hr•sq ft•°F (W/m•K)
A-6	2/27/86	3:00	45.1 (7.3)	26.4 (-3.1)	18.6 (10.4)	35.7 (2.1)	26.68 (84.15)	1.38 *** (0.20)
A-6	3/3/86	2:05	90.4 (32.5)	72.3 (22.4)	18.1 (10.1)	81.4 (27.4)	26.60 (83.92)	1.42 *** (0.21)
A-6	3/4/86	1:50	118.2 (47.9)	100.4 (38.0)	17.8 (9.9)	109.3 (43.0)	26.58 (83.80)	1.44 *** (0.21)

* Measured in accordance with ASTM Designation: C177 using a guarded hot plate.
** Specimens were cast 2/14/86.
*** Average effective thickness of specimens (distance between thermocouples) was 0.965 in. (24.6 mm).

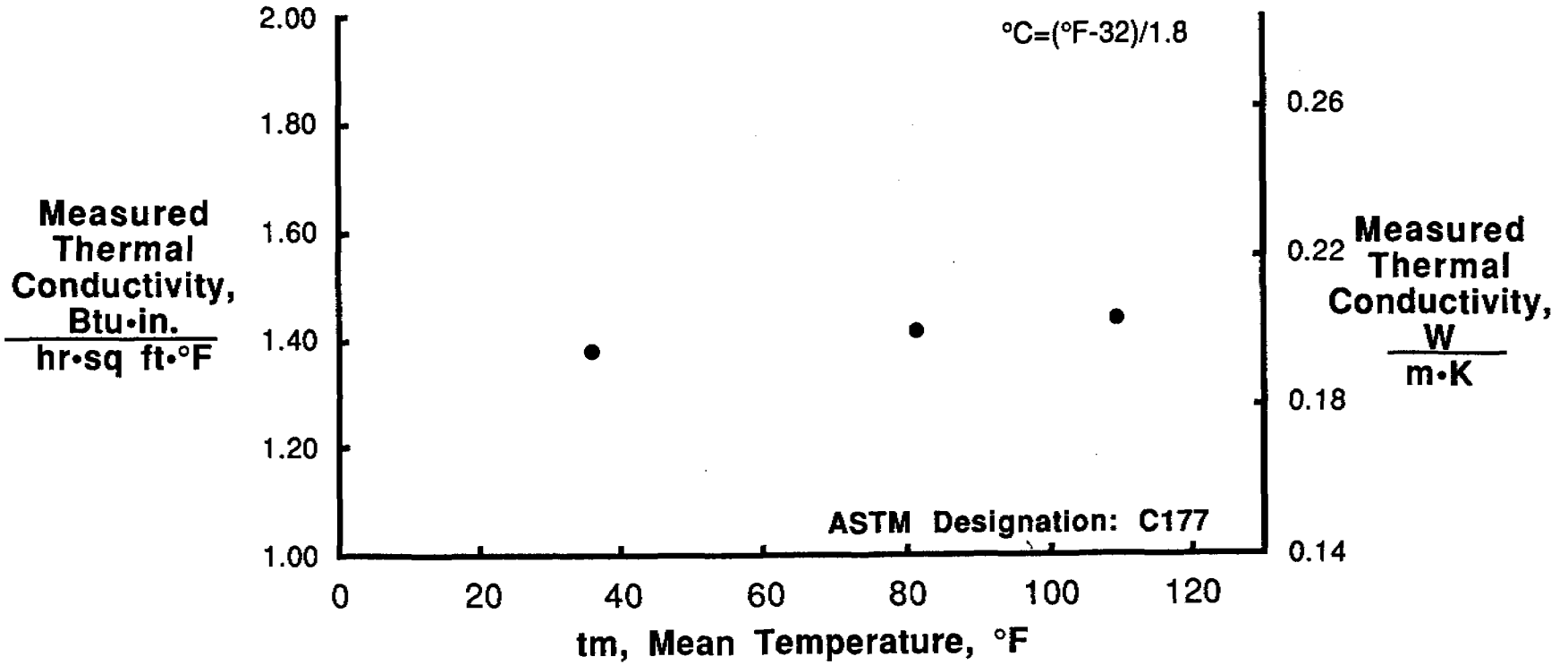


Fig. 17 Measured Thermal Conductivity of Polymer Concrete Specimens

SUMMARY AND CONCLUSIONS

An investigation was undertaken to develop a portland cement concrete with a unit weight of less than 50 pcf (800 kg/m^3), a compressive strength of 1000 to 1500 psi (6.9 to 10.3 MPa), and a thermal conductivity of about 1.5 $Btu \cdot in./hr \cdot ft^2 \cdot °F$ (0.22 W/m•K). These requirements were met using a newly developed aggregate from the 3M Company. The average strength actually obtained with this aggregate was approximately 2000 psi (13.8 MPa), well in excess of the requirement, and suitable for walls in low-rise buildings.

The developed concrete has an air-dry unit weight of approximately 50 pcf (800 kg/m^3) and a measured thermal conductivity of 1.6 $Btu \cdot in./hr \cdot ft^2 \cdot °F$ (0.23 W/m•K) at 75°F (24°C). Thermal conductivity of the lightweight concrete is 1/10th that for normal weight concrete.

Concrete thermal and physical properties were measured on small-scale specimens. Results were presented for thermal conductivity, thermal diffusivity, specific heat, compressive strength, splitting tensile strength, and modulus of elasticity. Test results indicate the concrete is suitable for walls in low-rise buildings.

Two full-size walls were cast of this concrete for subsequent testing in CTL's calibrated hot box facility. No problems were encountered in casting and consolidating these panels in a horizontal position. Thus an obvious use for the material would be in precast or tilt-up panel construction.

Rheology of the material indicates that consolidation in a vertically cast wall might be more difficult. However this was not investigated.

A second investigation was undertaken to develop a polymer concrete having thermal conductivity and compressive strength properties of about 1.0 Btu•in./hr•ft^2•°F (0.14 W/m•K) and over 3000 psi (21 MPa), respectively. Such concrete would be used as a thermal break material in buildings. Five polymer materials were investigated for use with the 3M aggregate. The best combination obtained was a unit weight of 49.6 pcf (794 kg/m^3) and compressive strength of 3020 psi (20.8 MPa). Thermal conductivity of the concrete was 1.4 Btu•in./hr•ft^2•°F (0.21 W/m•K) at 75°F (24°C). Additional work is needed to determine whether it is possible to meet the objective polymer concrete requirements.

REFERENCES

1. Larson, S. C., and Van Geem, M. G., "Structural Thermal Break Systems for Buildings - Feasibility Study," Oak Ridge National Laboratory Report No. ORNL/Sub/84-21006/1, Construction Technology Laboratories, Inc., Skokie, 1987, 88 pages.

2. Van Geem, M. G., "Structural Thermal Break Systems for Buildings - Heat Transfer Characteristics of Lightweight Structural Concrete Walls," Oak Ridge National Laboratory Report No. ORNL/Sub/84-21006/3, Construction Technology Laboratories, Inc., Skokie, to be published.

3. "Guide for Cast-in-Place Low Density Concrete," ACI 523.1R-67, American Concrete Institute, Detroit, 1967.

4. Annual Book of ASTM Standards, American Society for Testing and Materials, Philadelphia, 1987.

5. "Building Code Requirements for Reinforced Concrete (ACI 318-81)," American Concrete Institute, Detroit, 1987.

6. "Guide for Structural Lightweight Aggregate Concrete," ACI 213R-79, American Concrete Institute, Detroit, 1979.

7. Larson, S. C. and Van Geem, M. G., "Surface Temperature Measurement Techniques for a Calibrated Hot Box Test Specimen," Report No. ORNL/Sub/79-42539/7 prepared for Oak Ridge National Laboratory, Construction Technology Laboratories, Portland Cement Association, Skokie, IL, 1986, 78 pages.

8. Van Geem, M. G., Fiorato, A. E., and Julien, J. T., "Heat Transfer Characteristics of a Normal Weight Concrete Wall," Report No. ORNL/Sub/79-42539/1 prepared for Oak Ridge National Laboratory, Construction Technology Laboratories, Portland Cement Association, Skokie, IL, 1983, 89 pages.

9. Handbook for Concrete and Cement, U.S. Army Waterways Experimental Station, Vicksburg.

10. Whiting, D., Litvin, A., and Goodwin, S. W., "Specific Heat of Selected Concretes, "Journal of the American Concrete Institute, July 1978, pages 299-305. Also PCA Research and Development Bulletin RD058.

11. Van Geem, M. G. and Fiorato, A. E., "Heat Transfer Characteristics of a Low Density Concrete Wall," Report No. ORNL/Sub/79-42539/3 prepared for Oak Ridge National Laboratory, Construction Technology Laboratories, Portland Cement Association, Skokie, IL, 1983, 89 pages.

REFERENCES (continued)

12. Cruz, C. R. and Gillen, M., "Thermal Expansion of Portland Cement Paste, Mortar, and Concrete at High Temperatures," Fire and Materials, Vol. 4, No. 2, 1980. Also PCA Research and Development Bulletin RD074.01T.

13. Design and Control of Concrete Mixtures (EB001.12T), Portland Cement Association, Skokie, IL, 1979.

APPENDIX A: PORTLAND CEMENT COMPOSITION

Reprinted from
Design and Control of Concrete Mixtures (EB001.12T),
Portland Cement Association, Skokie, IL, 1979, pages 16-17

CHAPTER 2

Portland Cements

By definition portland cements are hydraulic cements, that is, they set and harden by reacting chemically with water. The process, called hydration, combines cement and water to form a stonelike mass.

The invention of portland cement is generally credited to Joseph Aspdin, an English mason. In 1824 he obtained a patent for his product, which he named portland cement because it produced a concrete that was the color of the natural limestone quarried on the Isle of Portland, a peninsula in the English Channel west of the Isle of Wight. The name has endured and is used throughout the world, with many manufacturers adding their own trade or brand names. The first portland cement made in the United States was produced at a plant in Coplay, Pa., in 1872.

MANUFACTURE OF PORTLAND CEMENT

Portland cement is produced by pulverizing clinker consisting essentially of hydraulic calcium silicates and usually containing one or more forms of calcium sulfate as an interground addition.

Materials used in the manufacture of portland cement must contain appropriate proportions of lime, iron, silica, and alumina components (Table 2-1). During manufacture, analyses of all materials are made frequently to ensure a uniformly high quality portland cement. Steps in the manufacture of cement by the dry process are illustrated in the flow chart on the following pages. While the operations of all cement plants are basically the same, no flow diagram can adequately illustrate all plants. There is no typical portland cement manufacturing plant; every plant has significant differences in layout, equipment, or general appearance. Mechanical equipment is described in Reference 2-12.

Selected raw materials are crushed, milled, and proportioned in such a way that the resulting mixture has the desired chemical composition. Either a dry or a wet process is used. In the dry process, grinding and blending are done with dry materials. In the wet process the grinding and blending operations are done with the materials in slurry form. After blending, the ground raw material is fed into the upper end of a kiln. The raw mix passes through the kiln at a rate controlled by the slope and rotational speed of the kiln. Burning fuel (powdered coal, fuel oil, or gas) is forced into the lower end of the kiln where it produces temperatures of 2600°F to 3000°F (1400°C to 1650°C), changing the raw material chemically into cement clinker. Clinker chemistry and the manufacturing process are described in Reference 2-13.

The clinker is cooled and then pulverized. During this operation a small amount of gypsum or anhydrite is added to regulate the setting time of the cement. The finished pulverized product is portland cement. It is ground so fine that nearly all of it passes through a sieve with 40,000 openings per square inch (60 openings per square millimeter).

Table 2-1. Sources of Raw Materials Used in Manufacture of Portland Cement

Lime, CaO	Iron, Fe_2O_3	Silica SiO_2	Alumina Al_2O_3	Gypsum, $CaSO_4 \cdot 2H_2O$	Magnesia, MgO
Alkali waste	Blast furnace flue dust	Calcium silicate	Aluminum ore refuse	Anhydrite	Cement rock
Calcite	Clay	Cement rock	Bauxite	Calcium sulfate	Limestone
Cement rock	Iron ore	Clay	Cement rock	Gypsum	
Chalk	Mill scale	Fly ash	Clay		
Clay	Ore washings	Fuller's earth	Copper slag		
Fuller's earth	Pyrite cinders	Limestone	Fly ash		
Limestone	Shale	Loess	Fuller's earth		
Marble		Marl	Granodiorite		
Marl		Ore washings	Limestone		
Seashells		Quartzite	Loess		
Shale		Rice hull ash	Ore washings		
Slag		Sand	Shale		
		Sandstone	Slag		
		Shale	Staurolite		
		Slag			
		Traprock			

Note: As a generalization, probably 50% of all industrial byproducts have potential as raw materials for portland cement manufacture (Reference 2-13).

APPENDIX B: 3M MACROLITE CERAMIC SPHERES DATA SHEET

Macrolite™ Ceramic Spheres

Preliminary Data Sheet

Effective: January 1, 1987

Description

Macrolite™ Ceramic Spheres are inert, low density spheres containing a multiplicity of minute independent closed air cells surrounded by a unique tough outer shell. The spheres are impermeable to water and other fluids and, being ceramic, the spheres are functional at extremely high temperatures. The outer surface can be altered to provide other physical and chemical properties.

Physical Properties:

	Sphere Size Range			Bulk Density		Specific Gravity*		Collapse Strength**	
Sphere type	U.S. Mesh	Millimeters	Inches	Nominal g/cc	Nominal #/ft.^{3}	Nominal g/cc	Nominal #/ft.^{3}	Nominal psi 10%	Nominal psi 20%
ML 535	1/2" to 3.5	12.7 - 5.7	0.50 - 0.22	0.30	19	0.58	36	3200	4200
ML 357	3.5 to 7.0	5.7 - 2.8	0.22 - 0.11	0.34	21	0.62	39	3600	4600
ML 714	7.0 to 14.0	2.8 - 1.4	0.11 - 0.06	0.40	25	0.77	48	4400	5400
ML 1430	14.0 to 30.0	1.4 - 0.6	0.06 - 0.02	0.45	28	0.85	53	5400	6400
ML 3050	30.0 to 50.0	0.6 - 0.3	0.02 - 0.01	0.48	30	1.05	66	7000	8000

* ASTM D 2840 (air comparison pycnometer)

** Isostatic pressures were measured in accordance with ASTM D 3102 using glycerol in place of water. Isostatic pressures near these values will cause breakage. In actual use, compressive and shear stresses should be kept at levels to ensure acceptable ceramic sphere survival.

Color:	Taupe, Brown to Grey
Odor:	None
Surface Characteristics:	Normal - Slightly Alkaline, Hydrophilic, Anionic
	Optional - Hydrophobic, Cationic
Thermal:	Stability - 1100°C (2000°F)
	Conductivity - 0.67 to 0.86 BTU/IN/FT^2/HR/°F @ 115°F
Moisture Absorption:	Less than 0.5% by weight
Health:	A Material Safety Data Sheet (MSDS) is available upon request.
Specifications:	Values reported here are typical properties, not to be used for specifications. For more specifications or more information, please contact your local representative or the St. Paul Office (1-800/225 1402 or 612/733 0350).

Litho in U.S.A.

Industrial Mineral Products Division/3M

Building 225-2N-07, 3M Center
St. Paul, Minnesota 55144-1000
612/733 0350
800/225 1402

Macrolite™ Ceramic Spheres

Product Information

3M

Potential Uses

Macrolite™ Ceramic Spheres are ideally suited for applications where economy and high volume are desired. Macrolite properties may be altered for specific applications including specialty coatings of organic and/or inorganic materials. Potential applications include (but are not limited to):

- Filtration
  - — Liquid Buoyant Media
- Controlled-Size Aggregates For:
  - — Low Density Oil Well Cements, Drilling Muds, Proppants
  - — Lightweight Structural Concrete
  - — Lightweight Pre-Fab Concrete Units
  - — Castable and/or Gunning Refractories
  - — Insulative Bricks and Blocks
  - — Gypsum Wallboard
  - — Roofing Systems
- Fillers For:
  - — Paint and Coatings
  - — Sealants
  - — Asphalt or Rubber
  - — Fire Protection Systems
  - — Boat Construction and Repair
- Explosives — Gel Slurry Sensitizers
- Abrasives
- Catalyst Support
- Vacuum Mold Fabrication
- Energy Management — Auto Body Structures

Litho in U.S.A.

Industrial Mineral Products Division/3M

Building 225-2N-07, 3M Center
St. Paul, Minnesota 55144-1000
612/733 0350
800/225 1402

3M