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Assessment of the Thermal and Physical Properties of Masonry Block Products

Rudolph Valore, Jr.
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ASSESSMENT OF THE THERMAL AND PHYSICAL PROPERTIES OF MASONRY BLOCK PRODUCTS

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FOREWORD

This is one of a series of reports to be published describing research, development, and demonstration activities in support of the National Program for Building Thermal Envelope Systems and Materials. The National Program involves several federal agencies and many other organizations in the public and private sectors who are addressing the national objective of decreasing energy wastes in the heating and cooling of buildings. Results described in this report are part of the National Program through delegation of management responsibilities for the DOE lead role to the Oak Ridge National Laboratory.

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This report was prepared by Steven Winter Associates, Inc. (SWA) in conjunction with its consultants Rudolph Valore, Jr. and Arnold Caputo, under subcontract to Oak Ridge National Laboratories/Martin Marietta Energy Systems, Inc. and with the sponsorship of the U.S. Department of Energy (USDOE).

Steven Winter Associates, Inc. developed the workplan and oversaw its implementation. SWA took a lead role in assessing the geographic distribution, quantity and physical characteristics of the US masonry block production and was responsible for the building code analysis section. The formatting of the thermal properties data used in the study was also undertaken by SWA. Finally, SWA contributed to the bibliographic searches and edited and produced the report. These aforementioned activities were directed by Adrian Tuluca, with assistance from Steven Bales. Deane Evans was principal-in-charge.

Rudolph Valore had a major role in this work, being responsible for the development of the thermal data and test recommendations, and contributing to the building code analysis chapter.

Arnold Caputo provided industry liaison and technical input to the statistical analysis of U.S. masonry block production.

Dr. David McElroy of ORNL provided subcontract management and technical guidance to the study. William Gerken of USDOE imparted overall project direction and contributed with valuable technical criticism during the course of the study. The authors are grateful for the thorough review of the draft report by Dr. David McElroy, William Gerken and Dr. D.W. Yarbrough, who through their comments helped improve the quality of the work.

The assistance of Kevin Callahan and Robert VanLaningham of the National Concrete Masonry Association, as well as the support of Robert Beiner of the International Masonry Institute in performing the industry-wide survey is also gratefully acknowledged.

EXECUTIVE SUMMARY

The objective of this study was to assess the current knowledge on the thermal and physical properties of concrete masonry units and fired clay bricks, and to outline directions for further research. In particular, it was attempted to:

A) Examine the extent to which the thermal properties of masonry blocks are covered by U.S. building codes and standards.

B) Uncover the areas where the knowledge on the thermal properties of masonry units is incomplete, or where the data appear to be inconsistent.

C) Suggest improvements to test procedures currently in wide use and propose the fine-tuning of alternate, less expensive test procedures.

D) Suggest testing programs designed to fill in the gaps identified above.

E) Characterize masonry units representative of U.S. production.

Building Codes and Standards: U.S. engineering handbooks, building codes, and building standards suffer from a cursory treatment of the thermal properties of masonry block products. The ASHRAE Handbook of Fundamentals (1985) does not cover many of the blocks currently in use and does not fully reflect the variation in density, aggregate composition and thermal conductivity encountered in modern production. Furthermore, there is no information on the effect of moisture on thermal conductivity.

UBC, NBC, SBCCI and BOCA recognize the fact that materials with "thermal mass"* have a different effect on space conditioning energy use than thermal insulation materials (e.g. glass fiber, cellulose, polystyrene etc.), but do not indicate how to account for this difference. Only the building codes of California and Florida attempt a thorough approach to the thermal properties of masonry products, but they still do not fully cover the thermal properties of concrete blocks and clay bricks.

---

* Materials with relatively high volumetric heat capacity and relatively high thermal conductivity, such as concretes and fired clays

Of the building codes of other countries, the USSR SNiP is the most comprehensive and most reliable in providing data on masonry products. This code is clearly more up-to-date than its U.S. counterparts. It is concluded that there is a strong need for revision of all U.S. engineering handbooks, building codes and standards with respect to the thermal properties of concretes and fired clays in general, and with regard to the thermal properties of masonry block products in particular.

Thermal Properties of Masonry Block Products: Part I develops thermal conductivity-density relationships (natural logarithm of thermal conductivity vs. square root of density) for masonry materials in the oven-dried condition, to constant weight at 220 to 230 F (105 to 110 C), for the following materials:

a. Concretes with ten types of lightweight aggregates and two types of normal weight aggregates

b. Autoclaved cellular concretes

c. Microporous calcium silicates

d. Neat cement foam concretes and cement pastes

e. Natural rocks of quartzitic and calcitic types

f. Solid clay bricks

Correlations based simply on linear plots of thermal conductivity versus density are also developed for loose fills in masonry:

a) Perlite

b) Vermiculite

c) Expanded clay and shale

d) Expanded slag

e) Sand and gravel

For 13 types of lightweight concretes, the mean deviation of values calculated from linear regression curves in relation to test values upon which the curves are based was 7% for about 700 tests. The coefficients of determination (square root of correlation coefficient) averaged 0.92. It is probable, therefore, that the calculated thermal conductivity has a greater validity in any given case than a single test value based upon a small specimen.

Normal weight concretes exhibit a poor correlation of thermal conductivity with density, because there is a wide variation in the

thermal conductivities of rocks that constitutes normal weight aggregates. It is proposed that the thermal conductivity of normal weight concrete be derived using the cubic model (Russell, 1935), which expresses the thermal conductivities of concretes as a function of the thermal conductivities of the cement paste matrix and aggregate, and of the absolute volume fraction of aggregate.

The linear thermal conductivity-density relationships for loose fills were found to be in good agreement with the underlying tests (coefficients of determination above 0.90).

Part I also summarizes moisture factors to adjust the oven-dry thermal conductivity to relative humidities encountered in the wall (60% and 80%). The factors are calculated based on a percentage increase in thermal conductivity for each 1% increase in moisture content, by weight. For lightweight concretes, the thermal conductivity is assumed to increase 4% to 6% per one percent of moisture. For normal weight concretes, the increase is assumed to be approximately 7% to 9%.

Part II gives examples of manual calculations for the U-values of multi-core blocks. It is concluded that the series parallel method of calculation is more accurate than the parallel method.

A listing of over 700 data points used in the study is provided, with the references to author, date and, when available, test method and specimen size.

Suggested New Test Research Directions: The data analyzed above were sometimes incomplete and sometimes inconsistent. Several reasons seem to have accounted for differences in thermal conductivity test results by different authors:

- The number of specimens of heterogeneous materials tested (concretes, clays) was sometimes too low, and did not compensate for variations in density;

- In some cases the specimens were not sufficiently thick (were less than 2 inches), and test results were influenced by the position of aggregate within the binder.

- The heterogeneities of the geometry of cored concrete blocks and clay bricks were not always reflected in the number and placement of thermocouples in the guarded hot-box tests of masonry walls.

- The effect of air gaps between the thermal element and specimen surface was not accounted for in some studies.

- In many instances, the moisture content of test specimens was not properly recorded.

It is suggested that the following research be considered to assess the state of current testing procedures:

a) Conduct round-robin tests with the following materials: normal weight concretes with granitic, carbonate and highly quartzitic aggregates; lightweight concretes with expanded shale, sanded expanded shale, scoria and pumice aggregates; cement-lime and masonry cement mortars; clay bricks. Concrete densities should encompass 60 to 140 lb/cu. ft. (1000 to 2250 kg/m^3). Brick densities should be in the 100 to 150 lb/cu. ft. range (1600 to 2400 kg/m^3).

b) Conduct round-robin tests for masonry walls. The concretes and clays used in the masonry units need to be first tested for thermal conductivity. The masonry units should then be ground, numbered and dry-stacked to build walls with taped joints. Dry-stacking eliminates the time needed to assess the moisture content in mortared walls; and different laboratories can test the same blocks.

It is suggested that the following test procedures be evaluated:

a) Reduce the effect of heterogeneities in hot-plate testing by averaging the test areas with a thin brass or copper shim stock adhered to the face of the specimen. Use a high thermal conductivity adhesive. Spot-weld or solder the ends of the thermocouple wires to the plate, small distances apart (Bittle and Taylor, 1984). Brass, or soldered copper and constantan foils could also be used for hot-plate tests to produce an averaging effect.

b) Use the needle probe (line heat source) method (Horai and Baldrige, 1969, 1971, 1972) to determine the thermal conductivity of rocks. The rock sample is pulverized and mixed with water to form a slurry. The measured thermal conductivity of the slurry may be used in the Cubic model equation to obtain the thermal conductivity of the rock. The rock thermal conductivity is used, in turn, to calculate the thermal conductivities of concretes, (cubic model).

   Alternately, the matrix "fluid" can be dry quartz sand (Drozdov, et al 1981), or small glass spheres, steel shot, zirconia or aragonite sand.

c) Investigate the use of the surface comparator method (Rousan and Roy, 1982) for carbonation-free rocks and clay bricks.

d) Use the screen-heater test method for testing masonry units, including single wythe assemblages of solid bricks and blocks, to determine the effects of moisture and atmospheric carbonation on density and thermal conductivity.

e) Use the comparative cut-bar method for bricks.

Suggested New Materials Research: In addition to test method related research, it is recommended that the following materials research be undertaken:

a) Investigate the effect of temperature on the thermal conductivity of concretes, fired clays, lightweight aggregates and portland cement pastes within the -40F to 120F range (-40C to 49C). Investigate the relationship between absolute temperature and thermal conductivity for these materials and for cored blocks made of these materials.

b) Investigate thermal conductance of hollow cores or slots in masonry units, over the - 40F to 120F range (-40C to 49C).

c) Further investigate the relationship between thermal conductivity and moisture content, by weight, for concretes and clay bricks.

d) Investigate the fluctuation of moisture levels in masonry walls when subjected to rainfall.

e) Develop thermal conductivity data on scoria, pumice, and fly ash aggregate concretes.

f) Develop information on the proper oven-dry regime for pumice concrete, so as to avoid removal of combined water.

g) Develop data on the effect of surface carbonation on the thermal conductivity of lightweight concretes.

h) Develop independent U-values for various configurations of rigid polystyrene inserts in concrete masonry units.

i) Develop thermal conductivity data for solid clay bricks in the 100 lb/cu. ft. to 150 lb/cu. ft. density range.

j) Assess the thermal conductivity of solid clay bricks in both longitudinal and transverse directions.

k) Investigate the magnitude of air infiltration through masonry walls and the effect of convective loops within cored masonry walls.

Characterization of Representative Masonry Units: Concrete masonry units (CMUs) and clay bricks were characterized from a statistical standpoint with respect to production quantities,

geographic distribution, geometry and composition.

Concrete Masonry Units:

a) About 1/2 of the U.S. concrete masonry units are made of concrete with a density higher than 125 lb/cu. ft., about 1/4 are made of 105-125 lb/cu. ft. concrete and about 1/4 are made of concrete with a density lower than 105 lb/cu. ft.

b) About 1/2 of all U.S. CMUs are 8 in. thick, about 1/5th are 12 in. thick, about 1/10th are 6 in. thick and 1/10th are 4 in. thick.

c) 2-core blocks account for over 90% of all 6 in., 8 in., 10 in. and 12 in. CMU production and for 1/3rd of the 4 in. block production. Of 4 in. blocks, 1/4th are solid and close to 1/2 are 3-cored.

d) The aggregates most used for CMUs are:

Normal weight - sand and gravel (quartzitic, carbonate, granitic)
- limestone (calcitic, dolomitic)

Intermediate weight
- limestone (oolitic)
- air cooled blast furnace slag
- power plant bottom ash or cinders

Lightweight
- expanded shale, clay and slate
- pumice
- scoria (volcanic cinders and volcanic slag)
- expanded blast furnace slag
- spontaneously burned colliery shale

e) 70% of all plants offer blocks with rigid insulation inserts, which comprise about one percent of total block production.

The U-value of a typical two-core 8 by 8 by 16 in. concrete block ranges from 0.54 for normal weight concrete (130-135 pcf) to 0.36 for a typical lightweight concrete (80 pcf) and to 0.31 for a lightweight concrete (60 pcf) made with very light aggregates. If the cores are filled with perlite, the U-values range from 0.36 for normal weight concrete (130-135 pcf) to 0.15 for a typical lightweight concrete (80 pcf) and to 0.11 for a lightweight concrete (60 pcf) made with very light aggregates.

Clay Bricks:

a) The most common brick sizes are:

2-1/4 in. by 3-5/8 in. by 7-5/8 in. or 8 in., produced by 55% of all plants.

2-3/4 in. by 3-5/8 in. by 7-5/8 in. or 8 in., produced by 21% of all plants.

3-5/8 in. by 3-5/8 in. by 11-5/8 in. produced by 17% of all plants.

b) Over ninety percent of all plant offer cores with one inch or more in at least one horizontal direction.

c) Of the brick types of point (a):

90% are nominally solid with coring of 25% or less
10% are classified as "hollow" with coring more than 25%

d) The restrained compressive strength of the 5 most produced bricks is (plants percentage):

75% between 8,000 to 9,000 psi
40% between 10,000 to 15,000 psi
About 25% below 8,000 psi
About 25% between 9,000 to 10,000 psi

This statistical information is intended to assist in structuring of testing programs which will generate results useful to the U.S. building industry.

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ASSESSMENT OF THE THERMAL AND PHYSICAL PROPERTIES OF MASONRY BLOCK PRODUCTS

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ABSTRACT

The objective of this study was to assess the current knowledge on the thermal and physical properties of concrete masonry units and fired clay bricks, and to outline directions for further research. In particular, they authors attempted to uncover the areas where thermal properties data are missing or are questionable, to define the type of testing required to fill in the gaps, and to characterize representative masonry blocks on which the testing should be undertaken.

U.S. building codes and standards were examined with respect to the thermal properties of masonry block products. It was concluded that the majority of these codes and standards contain insufficient and/or outdated information regarding concrete masonry units and fired clay bricks, thereby distorting the requirements for walls built with masonry units.

A comprehensive bibliography search was performed and the thermal properties data obtained were listed and analyzed. Relationships were derived between oven dry density and thermal conductivity for various concretes, clays, and loose fills. The relationship between moisture content and thermal conductivity was also examined. Areas with incomplete and/or contradictory information were identified.

Based on these data gaps and on data quality problems, new testing programs were recommended and improvements to current testing procedures were proposed. The study also suggests low-cost test procedures which could be applied to large numbers of masonry blocks.

Finally, the U.S. masonry block production was characterized in terms of its magnitude, geographic distribution, block geometry, and material composition, based on an industry survey. These data reveal the representative masonry block units in various groupings and are intended to be of use to researchers for establishing statistically significant testing programs.

1. INTRODUCTION

Masonry blocks are used in residential, commercial and industrial buildings and are produced in a variety of sizes and shapes (Figures 1.1a, 1.1b and 1.2). Approximately 3 to 4 billion concrete masonry units[1] and 7 to 9 billion clay bricks[2,3] are shipped annually to U.S. construction sites. Some examples of envelopes built with masonry blocks are presented in Figures 1.3a and 1.3b. While concrete and clay masonry units are widely used throughout the U.S., many aspects related to the thermal properties of masonry blocks are still not known or are surrounded by controversy. These uncertainties in the body of scientific knowledge have contributed to a relative lack of attention in building codes to the thermal behavior of concrete blocks and clay bricks.

This study attempts to synthesize the knowledge to date on the thermal properties of concrete blocks and fired clay bricks and suggests new research directions that might be worth pursuing in order to achieve a better understanding of heat transfer through masonry block envelopes. It is anticipated that the decision-making process, in both research and building code communities, will benefit from this and other similar efforts.

This report constitutes an account of work undertaken by Steven Winter Associates, Inc. (SWA) and its consultants Rudolph Valore and Arnold Caputo (the Project Team) pursuant to the requirements of subcontract 86X-22020V. The report describes the process and results of a survey and technical assessment of presently available physical and thermal property data for concrete and clay masonry block products commonly used in building wall construction.

Work on the project was conducted in two phases. The first was primarily a data acquisition effort in which the Project Team expanded its in-house data bases by means of an extensive literature search and through direct contact with industry associations, trade organizations, government agencies, laboratories and research stations, universities,

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1. National Concrete Masonry Association, 1984. NCMA Cost of Doing Business Study. National Concrete Masonry Association, Herndon, VA.
2. Mackay-Shields Economics, 1980. Regional Brick Consumption. Brick Institute of America, Washington, D.C.
3. Bureau of Census, 1980 through 1986. Clay Construction Products. U.S. Department of Commerce, Washington, D.C.

testing companies, brick and block producers, and individual researchers. A comprehensive bibliography is included in Chapter 6 of this report.

In the second phase, the aforementioned data base was analyzed, significant gaps in the information were identified and recommendations for further research and testing were developed. This report presents the results of both phases of the project. It is organized into six chapters and nine appendixes, each of which is described briefly below.

Chapter 2 presents a review of existing U.S. building codes and standards to determine how they currently account for the thermal properties of masonry block products. The limitations of these codes are delineated, and selected international codes are also briefly discussed for comparison purposes.

Chapter 3 provides a summary of currently available data on the thermal and physical properties of masonry block products. The summary is based on work performed by Rudolph Valore for the International Masonry Institute (IMI). The results of this IMI effort, which was initiated prior to the current study, are embodied in a report entitled "Thermophysical Properties of Masonry and its Constituents".

Chapter 4 reviews current U.S. testing procedures for masonry block products. Based on this review and taking into account the information gaps identified in Chapter 3, a series of specific recommendations as to future testing priorities are suggested.

Chapter 5 presents the results of a comprehensive survey of the masonry block industry in the U.S. The type, physical characteristics, geographical distribution and number of block products manufactured nationwide are delineated so that future testing can target those units that are statistically significant.

Chapter 6 presents one of the most comprehensive available bibliographies on the thermal and physical properties of masonry block products. Close to 300 relevant titles are included.

The Appendixes provide information considered too detailed to be incorporated into the report itself.

Appendix A presents samples of the Utah, Florida and California building energy codes.

Appendix B presents all the thermal conductivity data points on which the Chapter 3 analyses and results are based. These data points were extracted by SWA from papers referenced in Chapter 6 and were formatted into tables that could be directly used by other researchers and/or building code and standards organizations.

Appendix C uses the findings of a thermal conductivity study on unusual perlite concretes to verify the applicability of equations which relate thermal conductivity to density. Moisture content in concretes is also discussed.

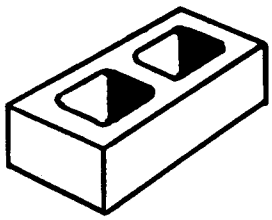
Appendixes D, E, F, and G contain brief notes intended to clarify the discussion of Chapter 4.

Appendix H exemplifies the calculation of thermal conductivity of concretes using the cubic model.

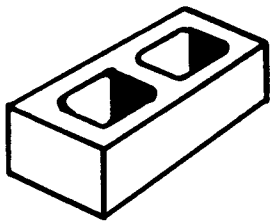
Appendix I presents the survey forms sent to concrete and clay brick producers.

Fig. 1.1a

CONCRETE MASONRY UNITS



6"x4"x16" PARTITION
DOUBLE ENDS



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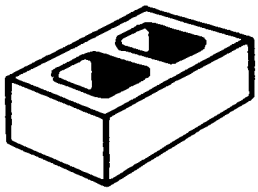
DOUBLE ENDS



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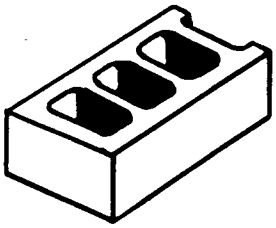
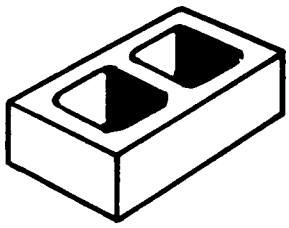
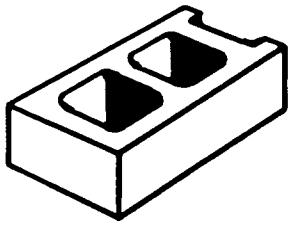
DOUBLE ENDS



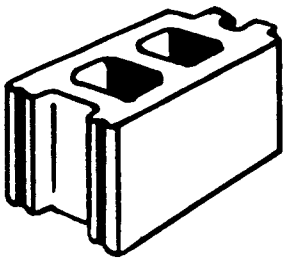
8"x4"x16"
HALF HEIGHT



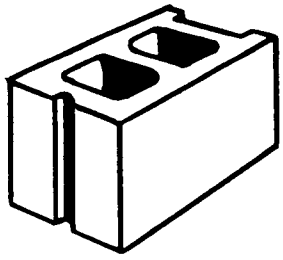
8"x4"x16"
HALF HEIGHT
DOUBLE END



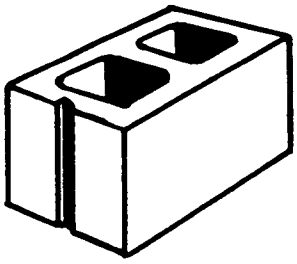
8"x4"x16"
HALF HEIGHT



8"x8"x16"
CONTROL JOINT



8"x8"x16"
STEEL SASH JAMB



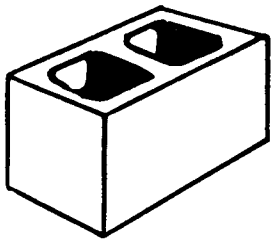
8"x8"x16" JAMB
3/4"x3/4" SLOT

NOTE : NOMINAL DIMENSIONS, SUBTRACT 3/8 IN. TO OBTAIN ACTUAL DIMENSIONS

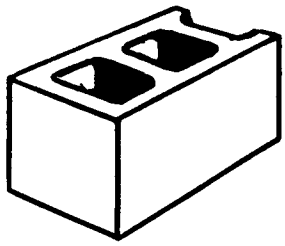
ADAPTED FROM THE "PASSIVE SOLAR CONSTRUCTION HANDBOOK",
STEVEN WINTER ASSOCIATES, 1984

Fig. 1.1b

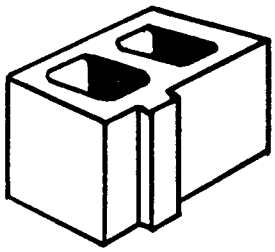
CONCRETE MASONRY UNITS



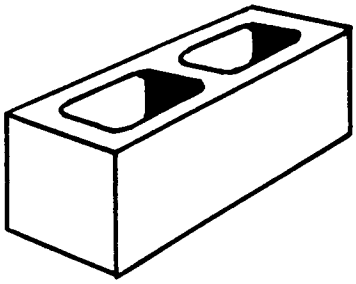
8"x8"x16"
DOUBLE END



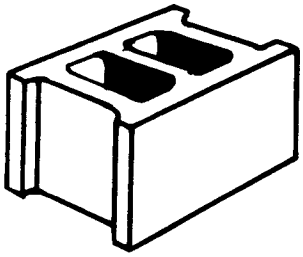
8"x8"x16"
REGULAR



8"x8"x16"
BOARD AND
BATTEN BLOCK



8"x8"x24"
DOUBLE END



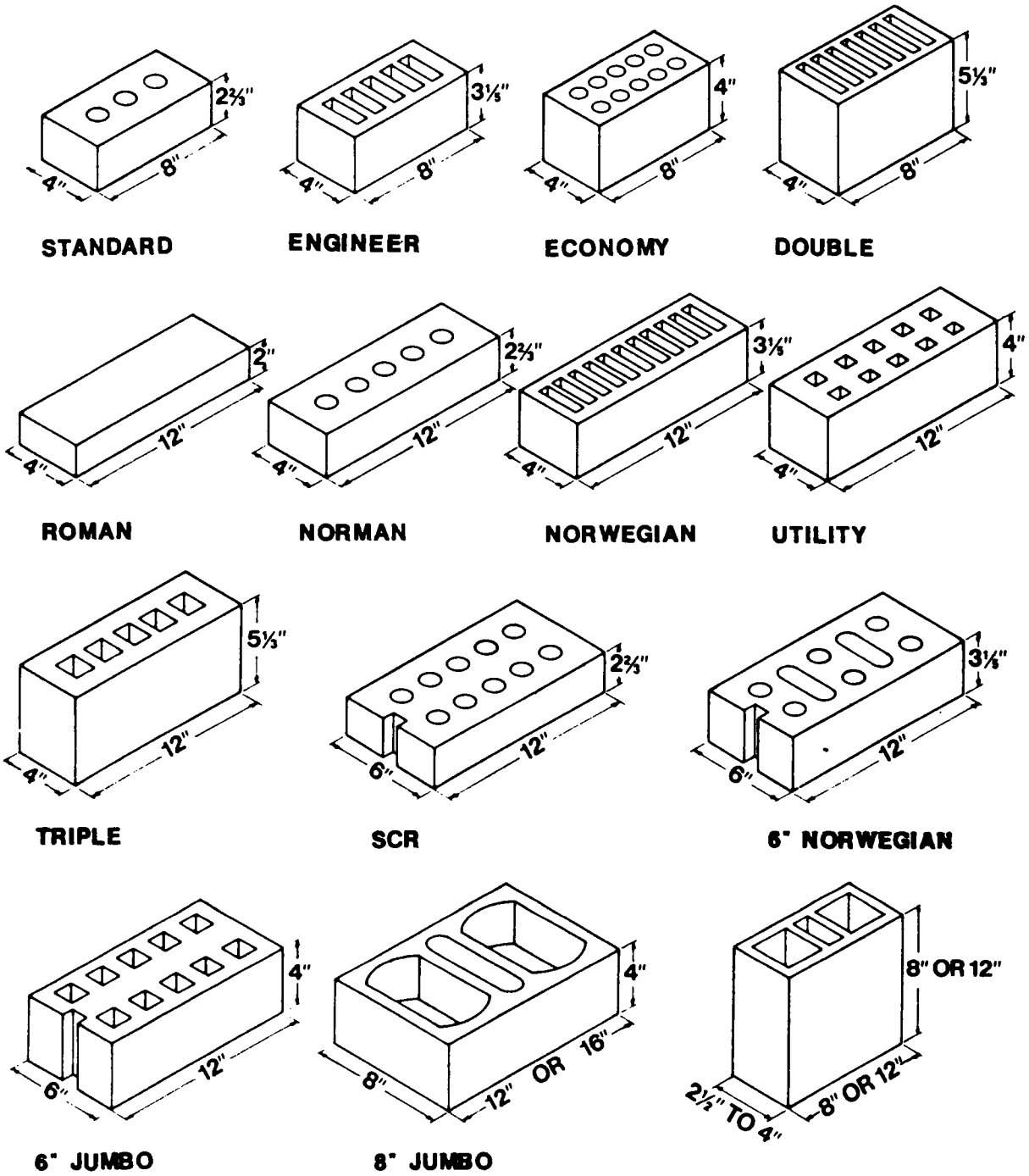
10"x8"x16"
STRETCHER

NOTE : NOMINAL DIMENSIONS, SUBTRACT 3/8 IN. TO OBTAIN ACTUAL DIMENSIONS

ADAPTED FROM THE "PASSIVE SOLAR CONSTRUCTION HANDBOOK",
STEVEN WINTER ASSOCIATES, 1984

Fig. 1.2

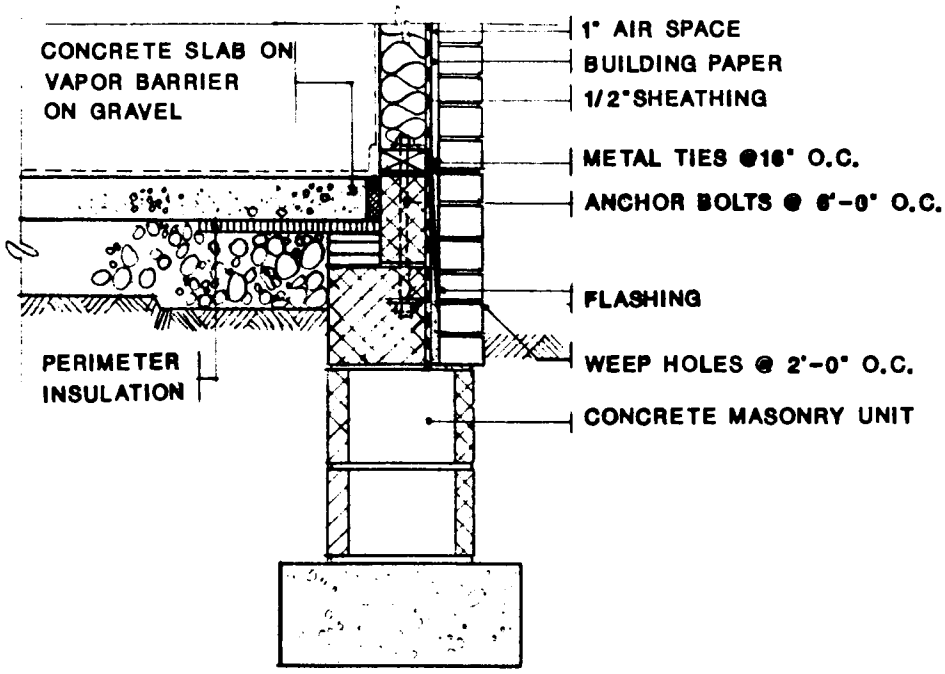
CLAY BRICKS



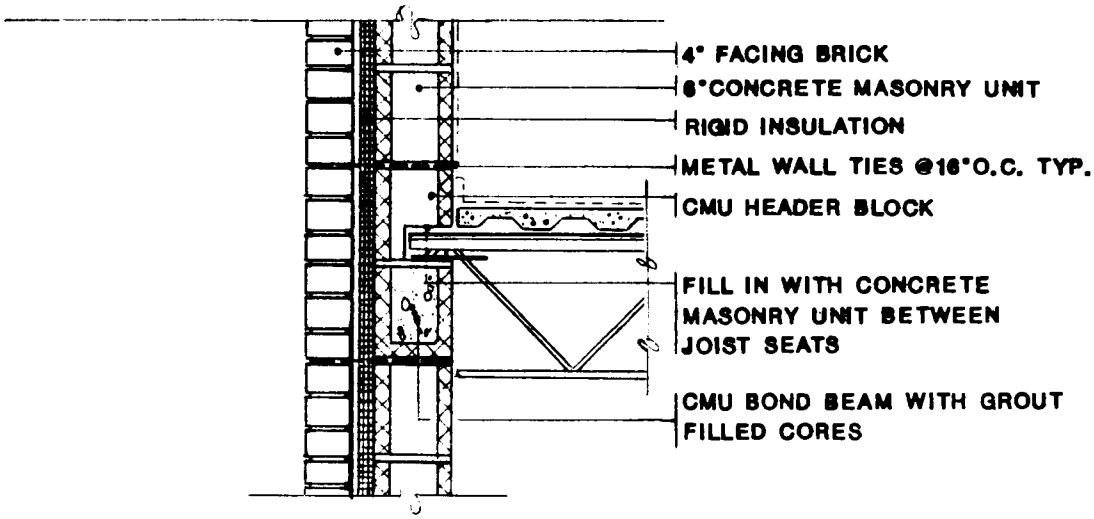
NOTE: NOMINAL DIMENSIONS, SUBTRACT 3/8 IN. OR 1/2 IN.TO OBTAIN ACTUAL DIMENSIONS
ADAPTED FROM THE "TECHNICAL NEWS-10B, APRIL 1986", BRICK INSTITUTE OF AMERICA

Fig. 1.3a

EXAMPLES OF MASONRY BLOCK CONSTRUCTION

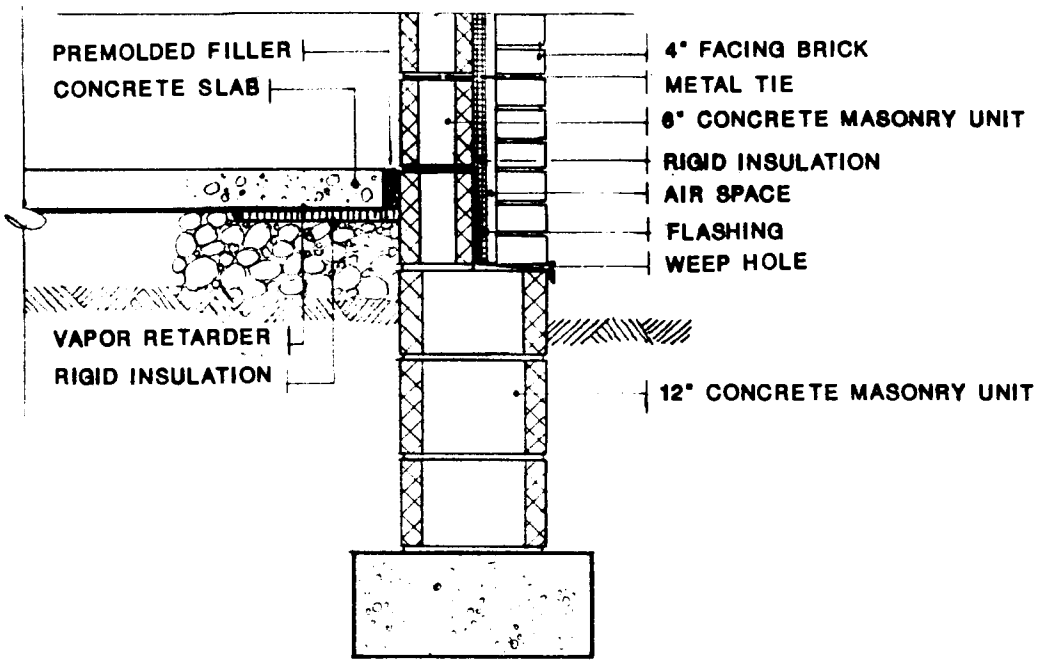


WOOD FRAME WITH BRICK FACING EXTERIOR WALL
SCALE 3/4"=1'-0"

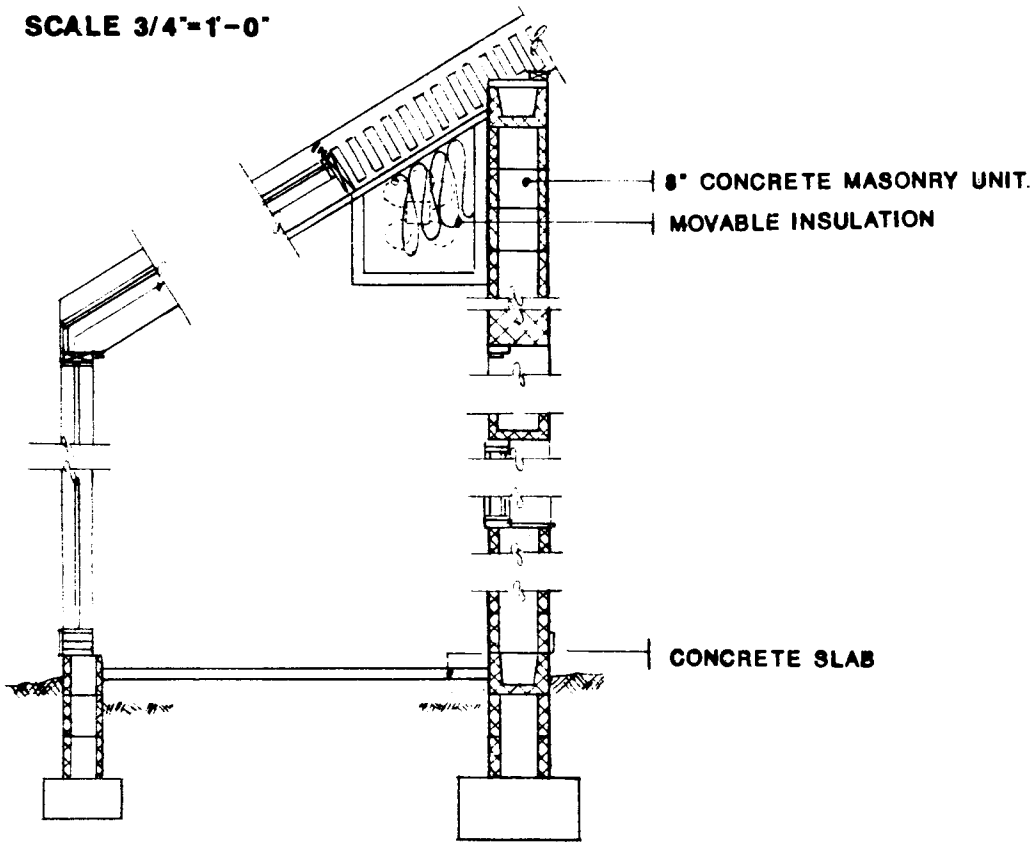


CONCRETE MASONRY UNIT WITH BRICK FACING EXTERIOR WALL
SCALE 3/4"=1'-0"

Fig. 1.3b
EXAMPLES OF MASONRY BLOCK CONSTRUCTION



CONCRETE MASONRY UNIT WITH BRICK FACING EXTERIOR WALL
SCALE 3/4"=1'-0"



CONCRETE MASONRY UNIT FACING LOAD BEARING WALL

2. BUILDING CODES AND STANDARDS

This section documents the status of building codes and standards with respect to thermal properties of masonry block products. It is concluded that materials with high volumetric heat capacity are incompletely, and often incorrectly covered and that there is a strong need for diffusion of sound scientific data into all U.S. codes and standards.

2.1 DEFINITIONS

The ASHRAE Handbook of Fundamentals (1985 Edition, Chapter 23) defines THERMAL CONDUCTIVITY as "the thermal transmission through conduction only through a unit area of a thermally homogenous and isotropic material in a direction perpendicular to the surfaces, with a temperature gradient of unity between the surfaces". Although not specifically mentioned in the ASHRAE definition, the thermal conductivity refers to unit thickness (1 inch or 1 meter).

THERMAL TRANSMISSION, in turn, is defined as "the quantity of heat flow from all mechanisms" in unit time, under the conditions prevailing at that time". For most building materials thermal transmission occurs by a combination of heat transfer modes. Specifically, solid thermal conduction and radiation are prevalent in solid masonry units. As a result "the measured property of these materials should be referred to as EFFECTIVE OR APPARENT THERMAL CONDUCTIVITY" (ASHRAE Handbook of Fundamentals, 1985). However, for reasons of brevity in expression, the effective thermal conductivity is referred to in this report by using the term thermal conductivity.

The symbol used for thermal conductivity is the Greek letter LAMBDA (formerly k in the U.S.). The units for thermal conductivity are Btu/h-ft^2-(F/in.) (U.S. or formerly British units) or W/m-K (SI units).

THERMAL CONDUCTANCE is defined as "the thermal transmission through unit area of a particular body or assembly with defined surfaces when a unit average temperature difference is established between the surfaces. Although not specifically mentioned by this definition, the thermal conductance refers to unit time (hr.). The symbol used for thermal conductance is C. The units for thermal conductance are Btu/h-ft^2-F (U.S. or formerly British units) or W/m^2-K (S.I.).

THERMAL RESISTANCE is defined as "the reciprocal of thermal conductance". The symbol is R, and the units are h-ft^2-F/Btu (U.S. or formerly British Units) or m^2-K/W (S.I.).

THERMAL TRANSMITTANCE is defined as "the thermal transmission through unit areas of a particular body or assembly (including its boundary films), where the difference between the fluid temperatures on either side of the body or assembly is unity". Although not specifically mentioned by this definition, the thermal transmittance

is measured in unit time (hr.). The symbol used for thermal transmittance is U, and the units are Btu/h-ft^2-F (U.S. or formerly British units) or W/m^2-K (S.I.).

In presenting and analyzing data on thermal conductivity, this study reports the "oven-dry" bulk density of the material, obtained by drying to constant weight, usually not exceeding 48 hours, at 220 to 230 deg. F (105 to 110 deg. C). The symbol for density is the Greek letter p (RHO).

THERMAL MASS is a term employed by energy use analysts and building code officials to designate the ability of some "high density" materials to store and release heat, usually within a 24-hr diurnal cycle, and usually in a manner conducive to reduced space conditioning energy consumption. Because the term is not rigorously defined, it is described below indirectly by delineating the manner in which thermal mass materials reduce energy consumption.

A wall built with masonry block components will tend to reduce the space conditioning energy use in climates where the outside air temperature swings daily, over extended periods of time, above and below the thermostat setpoint; and/or also in climates with a high level of insulation during periods when the outside air temperature is below the thermostat setpoint. The energy use reduction is achieved by storing heat into the wall during the period when the outside air temperature is above the thermostat setpoint, and by releasing this heat into the conditioned space when the outside air temperature falls below the thermostat setpoint. Another mechanism for reducing energy consumption is to store excessive heat caused by solar radiation captured through windows, and to release this heat into the space during the evening and night, when the outdoor air temperature is below the thermostat setpoint.

The capacity to store thermal energy is directly proportional to density and specific heat. There is considerable variation in density among building materials; the concretes and fired clays that are used in masonry block products have a relatively high density range when compared to insulation materials (e.g. glass fiber, mineral wool, urethane, polystyrene, polyisocanurate). There is, however, little variation in specific heat among building materials.

The rate of thermal energy storage and release is dependent on the thermal conductivity of materials, and, in the case of non-homogenous, non-isotropic materials (e.g. concretes and fired clays), on their apparent thermal conductivity. Masonry block products have higher thermal conductivities than insulation materials.

Because materials with high density are called "massive", and because these materials have a thermal effect on conditioned spaces, they are referred to as THERMAL MASS materials. Walls using masonry units are therefore designated as "thermal mass" walls. It is worth noting that the designation of thermal mass is applied in general only to those materials which, due to the combination of thermal conductivity, specific heat and density, tend to significantly reduce space conditioning energy use. Steel, for example, has a high density, but because of its very high thermal conductivity it

increases the space conditioning energy use in buildings. As a results, steel is not referred to as a "thermal mass" material.

2.2 GENERAL PROBLEMS IN CODES STANDARDS WITH RESPECT TO HEAT TRANSFER THROUGH MASONRY BLOCKS

Heat transfer through masonry blocks is a complex phenomenon. Concretes are formed of a hardened cement paste, aggregate and air pores. The apparent thermal conductivity of a concrete depends on the thermal conductivities of the cement paste and of the aggregates, as well as on the thermal radiation across the air pores; it also depends on the volumetric ratio of the aggregate to cement paste, and on the size and shape of the aggregate, which in turn determine the size and shape of the air pores. Concrete blocks have cores of varying shapes and sizes, and these cores modify the heat transfer across concrete masonry units (CMU). Fired clay bricks are formed of fired clay, pores and, most often, of cores of varying sizes. The apparent thermal conductance varies with direction (length, width, depth) in bricks, because of the manufacturing process. The thermal conductance is also influenced by core configuration.

All masonry blocks contain moisture in quantities which vary with ambient conditions. This moisture increases their apparent thermal conductance, by comparison to the "oven-dry" state. Furthermore, increases in temperature tend to increase the thermal conductance of masonry block constituents, over the range of temperatures experienced by buildings.

It is apparent that all US building codes and standards suffer from a cursory treatment of the thermal and physical properties of thermal mass materials, especially relative to moisture content and mineralogic composition of the aggregates. The ASHRAE Handbook of Fundamentals (1985), contains much outdated and incomplete information. With the exception of 7 U.S. states, no specific method for calculating the benefits of thermal mass construction is provided in state energy codes. Where guidance is offered, important construction aspects which influence dynamic heat transfer are not present (e.g. position of insulation with respect to thermal mass). At this time only the California and Florida building codes attempt a thorough treatment of thermal mass walls, but even there one can find omissions with respect to material properties (moisture content, mineralogic composition) and climate dependence (variation of conductance with temperature), as well as other simplifications specific to the two codes (see code synopsis below).

A discussion of the 1985 ASHRAE Handbook of Fundamentals data on thermal mass follows, with references to Austrian, British, French, Soviet Union and West German building codes. BOCA, NBC, SBCCI, UBC and several state building codes are also reviewed with respect to thermal mass.

It is concluded that there is a strong need for revision of all US codes and standards in order to incorporate realistic material and assembly properties.

2.3 THE 1985 ASHRAE HANDBOOK OF FUNDAMENTALS AND FOREIGN BUILDING CODES

Chapter 23 of the 1985 ASHRAE Handbook of Fundamentals lists R-values for concrete block and clay brick which are in some respects out of date and in others very meager.

Wall test data are given for oval-core block, apparently based on University of Minnesota and Portland Cement Association studies of the 1930's. Oval core blocks are no longer produced.

Data for modern rectangular core block walls, with cores empty or insulated, do not reflect the variations in density and thermal conductivity encountered in modern production, based on type, density and mineralogic composition of aggregate. The entire range of light weight aggregate concrete units is represented by units with a single density of about 85 pcf, irrespective of the fact that present production encompasses densities of 55 to 105 pcf and that the various aggregates used in concrete units include expanded shale, slate and clay; expanded slag; and pumice and scoria. Furthermore, the concretes may include supplementary natural aggregates such as siliceous sand, limestone, or granite. Also, thermal conductivity values either correspond to oven-dry conditions, thus underestimating the heat flux through masonry units subjected to weather, or are presented at unspecified moisture contents, thus making proper usage difficult. Even under oven-dry conditions, the ASHRAE data at higher densities for concrete are substantially incorrect (See Chapter 3, Table 3.2). Thermal conductivity is given for only one wall of "common" clay brick and only one wall of "face" clay brick. Similarly, only one value is presented for "cement mortar", which by itself is not used in US masonry wall construction. There are no values for cement-lime mortars.

Among various building codes of other countries, summarized in Table 2.1, the USSR SNiP II-3-79 (1986) is the most comprehensive. It covers over 60 types of light weight and other concretes, clay and silicate bricks, loose granular fills, natural building stones, and various types of insulations and it lists dry density, specific heat, oven-dry thermal conductivity and two other practical relative humidity exposure conditions (A, for protected masonry and B, for unprotected masonry). It also lists heat assimilation factors, and water vapor permeability.

The thermal conductivity correction for moisture content varies substantially among all these codes. The ASHRAE Handbook of Fundamentals, Chapter 23 (1985) gives no indication on how to convert oven-dry conductivities to design values. Column 3 of Table 2.1 presents thermal conductivities adjusted by a 5% moisture correction, by weight, for light weight concretes, and by a 7% moisture correction, by weight, for medium and heavy weight concretes, according to Valore (1980). Great Britain's CIBS uses a 3% and 5% moisture content, by volume, for protected and unprotected conditions, respectively. Since the relationship between thermal conductivity and

volumetric moisture content is influenced by density, a constant volumetric correction factor does not properly cover the range of densities. While its moisture correction is in general high, CIBS also uses thermal conductivity values that appear to be too low for oven-dry concretes. As a result, the two errors nearly cancel each other and come in close agreement to Valore's data (1980). There is currently interest in Great Britain to revise the CIBS.

West Germany's DIN 4108 assumes the thermal conductivity to increase by 6% for every 1% of moisture by volume.

The USSR SNiP assumes a 5% increase in thermal conductivity for each 1% increase in moisture, by weight. Condition "A" (protected wall) thermal conductivities are in average 20% higher than oven-dry thermal conductivities, and generally agree with findings by Valore (1980).

British, Austrian and French codes assume a 30% increase in thermal conductivity for the first 1% in volumetric moisture content. The increase in thermal conductivity is assumed to be 60% for the first 3% of moisture, by volume. These relationships are probably derived from Jakob and result in high thermal conductivities under normal operating conditions.

A comparison between thermal conductivity values listed in the different codes show a wide spread in differences. For example, a 1000 kg/m^3 concrete would have the following thermal conductivities, in Btu/h-ft^2-(F/in):

ASHRAE CHAPTER 23	ASHRAE CHAPTER 23 WITH VALORE (1980) CORRECTIONS	GREAT BRITAIN CIBS "PROTECTED"	WEST GERMANY DIN 4108	USSR SNIP "A"	AUSTRIA	FRANCE
1.7	2.05	2.1	2.6	2.3	2.6	2.3-3.2

The data in the ASHRAE Handbook of Fundamentals, Chapter 23 are in need of updating and expansion. Information on the effects of moisture on heat transfer are required, and on the thermal conductivity of mortars, some concretes and fired clays is needed.

TABLE 2.1 "EFFECTIVE" THERMAL CONDUCTIVITY OF LIGHT WEIGHT AGGREGATE CONCRETES PRESCRIBED IN BUILDING CODES [BTU/HR-SQ. FT.-(F/IN.)]**

Density***	US ASHRAE		Great Britain CIBS GUIDE A 3 (1980)		W. Germany DIN 4108	USSR SNIP II-3-79		Austria Catalog 1979	France Rules Th-K-77
pcf	Ch. 23 (x1.2) 5% moist. by wt. (Valore)		Protected 3% moist. by vol.	Exposed 5% moist. by vol.	"Practical values" 6% moist. by vol.	A 50-60% RH	B 60-75% RH		
150	—	—	12.7	13.9	14.6	10.4	11.1	16.0	12.1
144	9.0	12.0	—	—	—	—	—	—	12.1
137	(od)	(not od)	10.1	11.1	—	—	—	10.4	12.1
131	—	—	—	—	—	—	—	—	—
125	—	—	7.8	8.6	—	—	—	—	—
112	—	—	6.0	6.7	—	5.6	6.4	—	7.3*
100	3.6	(4.3)	4.2	5.1	5.1	4.7	5.5	—	5.9*-7.3*
94	—	—	—	—	4.6	—	—	4.25	5.9*
87	—	—	3.5	4.0	4.3	3.9	4.5	3.9	4.9-5.9*
81	2.5	(3.0)	3.1	3.4	3.9	—	—	3.55	4.9*
75	—	—	2.6	2.9	3.5	2.1	3.6	3.3	3.2*-4.9*
69	—	—	—	—	3.1	—	—	3.0	3.2*
62	1.7	(2.05)	2.1	2.3	2.6	2.3	2.8	2.6	2.3-3.2*
44	—	—	—	—	2.4	—	—	—	2.3
50	—	—	1.6	1.8	2.1	1.7	2.2	2.0	1.7-2.3
44	<(1.15)	<(1.4)	1.5	1.6	—	—	—	—	1.7
37	—	—	1.3	1.4	—	1.4	1.8	1.4	1.7
31	0.9	(1.1)	1.1	1.25	—	1.2	1.6	1.0	1.4
25	—	—	1.05	1.1	—	—	—	—	—
19	0.7	(0.85)	—	—	—	—	—	—	—

* Contains natural sand

** To convert Btu/hr-sq. ft. - (F/in) to W/m-K multiply Btu/h-sq. ft. - (F/in) values by 0.1442

*** To convert pcf to Kg/m^3 multiply pcf values by 16

TABLE 2.1 ADDENDUM

Explanation of Notations

1) U.S.	ASHRAE Handbook of Fundamentals, Chapter 23, 1986
2) Great Britain	CIBS Guide, A3 1980
3) USSR	SNIP II-3-79, Building Thermotechnics, Part II, Chapter 3 of Building Specifications and Regulations, 1986.
4) France	Unified Code of Practice, Rules Th-K-77, Rules for Calculating Practical Thermal Properties of Structural Components, Nov. 1977.
5) Austria	Hochbau Warmeschutz (Thermal Protection of Building Structures), Onorm B 8110, December 1974. (Also Hohlblocksteine (Hollow Blocks) Onorm B3206, July 1981 (refers to Onorm 8110).
6) West Germany	Thermal Protection in Building Structures; Heat Insulation and Heat Storage; Requirements and Directions for Planning and Execution, DIN4108, Part 2, Aug. 1981. (pp. 477-494); also Part 3, Protection from Climatic Moisture Conditions, pp. 494-505; and Part 4, Heat and Moisture Protection-Technical Requirements, pp. 506-523), Mauerwerk (Masonry) Kalender 1984, Ernst and Son, Berlin, 1984.

2.4 US STATE BUILDING CODES

In the design of energy efficient buildings, insulation and thermal mass can be combined in different ways to achieve the desired energy consumption. The effectiveness of thermal mass is influenced by the following factors:

- thermal and physical properties of the "mass" material; density, specific heat, and thermal conductivity,
- configuration of the masonry blocks: core shapes,
- configuration of the wall section: homogeneous or multi-layered (nonhomogeneous),
- type and position of wall insulation with respect to mass,
- thickness of mass layer, and
- ambient conditions: temperature, humidity, and their rate of change over time.

U.S. Codes and Standards agencies do not have a unified approach to thermal mass and its effects on energy consumption. The following is a short synopsis of thermal mass, as incorporated in state and national codes and standards.

A majority of states (25) do not specifically credit the effects of thermal mass on energy consumption. A typical reference to thermal mass follows:

> "In addition to the criteria set forth in this section, the proposed design may take into consideration the thermal mass of building components in considering energy conservation when approved by the Building Official."

This reference is also encountered in UBC, NBC, SBCCI and BOCA. A few states set specific procedures for accounting for the effects of thermal mass on space conditioning energy consumption. A brief discussion of their codes follows. It should be noted that, even when the thermal effect of masonry is addressed, the underlaying data suffer from the problems identified within the ASHRAE Handbook of Fundamentals.

The state of Nevada uses a mass correction factor which is determined by the weight of masonry wall construction in lbs./sq. ft. and the number of degree days. This approach is outlined in Chapter 10, paragraph 10.02.1.1 in the "Energy Conservation Standards for New Building Construction" for Nevada.

Quote:

10.02.1.1 In calculations required by heating criteria provisions of these standards, the U-value of masonry wall construction may be adjusted by a mass correction factor for determining the Uo value of the wall according to the following schedule:

Weight of Masonry Wall Construction lbs./sq. ft.	Mass Correction Factor 3500 Degree Days or Less	Mass Correction Factor More Than 3500 Degree Days
0-25.....	1.000	1.000
26-40.....	.850	.880
41-80.....	.750	.791
81 and above.....	.650	.775

End of quote.

This calculation does not take into account:

- o configuration of the wall section
- o type and position of wall insulation with respect to mass
- o thickness of mass layer

The state of Utah, like Nevada, uses a mass or "M" correction factor, to determine the influence of wall weight on the U-value for heating design. (The U-value of the wall is multiplied by the "M" factor to obtain the "corrected" U-value.) Degree days and weight of masonry wall are the parameters. The reference is made in paragraph 602.0 under Chapter 6, Building Design by Acceptable Practice in the "Utah Code for Energy Conservation in New Building Construction", and reads as follows:

> "The proposed design may take into consideration the thermal mass of a wall section by using the "M" factor in figure 6-8 based upon the appropriate heating degree day value."

The chart with the M factor is located in Appendix A.

The state of Florida has developed a residential Point System Method. Under this method, points are calculated for the envelope elements of an "As-Built" house and for a "Baseline"

house of the same configuration and orientation. The ratio of the total points calculated for the As-Built house to the total points calculated for the Baseline house is then multiplied by 100. The result must be 100 points or less in order to comply with the Code.

Based upon BLAST* computer simulations, a series of winter and summer points were developed. The magnitude of these points is determined by the R-value of the insulation in the wall, its location, and the configuration of the wall determine this multiplier. Energy conserving residences get few points, while "loose" houses obtain a higher number of points.

This analysis does not take into account:

- the case when insulation is integral with the mass
- the thickness of the mass
- the fact that two weight categories is too broad a classification

A sample of the point system is attached in Appendix A.

California ("New Residential Building Standards Energy Conservation Manual") evaluates the performance of thermal mass using two design criteria:

1) Minimum heat capacity based on the material thickness (up to a maximum of two inches), density and specific heat and

2) Minimum surface area ratio -- the ratio of the area of mass to the area of south-facing glazing. A specific set of calculations are outlined to determine Minimum Thermal Mass Requirement.

This analysis does not take into account:

- type and position of wall insulation

A sample of the California calculation procedure follows is attached in Appendix A.

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* BLAST is an energy use simulation program, similar to DOE-2.1

3. THERMAL PROPERTIES OF MASONRY BLOCK PRODUCTS

In recent years, costs of energy for heating and cooling buildings have produced increasingly concentrated study of heat losses through building envelopes and of means of reducing those losses. Testing of masonry walls for thermal transmittance (ASTM C236, 1985) is time-consuming and costly; properly performed tests provide data only for a particular wall tested under the conditions maintained in a test such as the guarded hot box test. It is not practicable to test all combinations of materials in a construction which may be of interest under various conditions of exposure. Instead, wall tests should serve only as anchor points, allowing interpolation or extrapolation for variation in materials properties and moisture contents.

To provide accurate estimates of heat transfer through masonry assemblages, data are required on the thermal conductivity of masonry constituents as function of material or mineralogic type, density and moisture content. Also required is an accurate and accepted method of calculation for thermal transmittance of walls of units with complex core geometry.

3.1 SUMMARY

Part I reviews* basic thermal conductivity-density relationships for masonry materials in the oven-dried condition when dried to constant weight at 220 to 230 F (105 to 110 C). Relationships are linearized for regression analyses by plotting the natural logarithm of thermal conductivity versus the square root of density for:

a. Concretes with ten types of lightweight aggregates and two types of normal weight aggregates

b. Autoclaved cellular concretes

c. Neat cement foam concretes and cement pastes

d. Natural rocks of various types

e. Solid clay bricks

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* Based on the 1987 study by Valore for the International Masonry Institute: "Thermophysical Properties of Masonry and its Constituents"

Correlations based simply on linear plots of thermal conductivity versus density are also developed for loose fills perlite, vermiculite, and expanded clay and shale.

A separate section is devoted to calculation of thermal conductivity of concretes as a function of the thermal conductivities of the cement paste matrix and aggregate, and of the absolute volume fraction of aggregate. Calculations are based on a cubic model (a cube of aggregate within a cube of cement paste matrix). This model was presented in 1935 by Russell for calculating the effect of porosity on the thermal conductivity of ceramic materials, and is used here for normal weight concretes because the thermal conductivities for these concretes cannot be predicted based on their densities alone. This poor correlation between thermal conductivity and density is due to the wide variations of thermal conductivity of the rocks which constitute normal weight aggregates. The cubic model is also used for calculating thermal conductivities of sanded* expanded clay and shale concretes as a function of (1) mineralogic type of sand; (2) absolute volume fraction of sand and (3) density of lightweight aggregate-cement paste "matrix". Correlations of calculated and test values are given for all these types of concretes. See Appendix H for sample calculation with the cubic model

Moisture contents of materials under "practical" conditions (i.e, in normal exposures rather than oven-dry conditions) in equilibrium with various mean relative humidities have also been compiled from numerous studies. Moisture factors for thermal conductivity were subsequently summarized from these tests, as increases in thermal conductivity for each one percent of moisture, by weight. The "practical" thermal conductivity values obtained from moisture corrections were then tabulated, for each type of material, as a function of density.

Part II of the International Masonry Institute (IMI) report describes the calculation of thermal conductance (C) and thermal transmittance (U) for masonry walls, using the "practical" thermal conductivity data developed in Part I. The calculation method used has been termed the "isothermal planes" method in the ASHRAE Handbook of Fundamentals (1985). Correlations of calculated versus test values of R or U are given for walls of North American large-core types of concrete blocks with cores empty and filled with loose granular insulation, and for walls of European types of multicore concrete and clay units.

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* A sanded lightweight concrete is one in which part of the lightweight aggregate is replaced by normal weight sand.

3.2 DATA SOURCES.

The total number of thermal conductivity test values cited in the IMI report is well over 1000. These data draw on studies by Valore at the National Bureau of Standards published in 1951, 1954 and 1956, which summarized earlier data of Rowley and Algren* (1937), Price and Cordon (1949), and Kluge et al (1949). Surveys by Lewicki (1967) and Arnold (1969) are comprehensive sources of thermal conductivity data developed by others, but primary sources cited have been relied upon where it has been possible to locate them. Books containing data on thermal properties of the entire range of lightweight concretes produced in Eastern Europe, which are applicable to North America and Western Europe as well, constitute another valuable source of information.

"Building Specifications and Regulations" (SNiP) of the U.S.S.R. for 1971, 1979 and 1986 list over 200 thermal conductivity values for lightweight aggregate and normal weight concretes having a wide range of densities. Data are given for materials in the oven-dry condition and for two "practical" moisture contents for each type of concrete. Thermal conductivity values are also given for cellular concretes, masonry mortars, clay and sand-lime brick masonry, and lightweight aggregate granular fills, as well as for numerous other materials. The SNiP values are not included in the correlations given in this report; they are used instead for comparison with correlations derived from actual test data from published papers or reports. In general, the agreement is very good.

Most of the recent data on thermal conductivity of masonry materials has come from Europe while most of the test data on thermal transmittance of masonry walls was developed in the United States.

Most of the thermal conductivity data were obtained by the guarded hot-plate (ASTM C177 or similar methods); the data of Saare and Jansson, and of Jonell on cellular concretes, and the data of Lentz and Monfore on cement pastes, natural rocks, and concretes were obtained by a "hot-wire" line heat-source method. The latter method has been used widely for soils, sands and granular fills. Heat-flow meters (ASTM C518) have been used for low-density granular fills and for some lightweight concretes, by Dynatech Scientific, Inc. and by Bech.

The data reviewed are listed in Appendix B.

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* Research of Rowley and Algren is comprehensive work well ahead of its time, covering thermal conductivity tests of lightweight aggregate and normal weight aggregate concretes, and clay brick and tile and concrete masonry thermal transmittance wall tests. Their thermal conductivity values are in excellent agreement with data from Western Europe and the Soviet Union, developed mainly since 1960.

3.3 PART I - THERMAL PROPERTIES OF MASONRY BLOCK PRODUCTS

Concrete and masonry are true composites and should be considered to be homogeneous only in a statistical sense. For this reason, lightweight concretes were separated according to aggregate type and then linear regression analyses were performed to relate thermal conductivity to oven-dry density for each type (e.g. Fig.3.1 through 3.7). Similar calculations were performed for fired clays (Fig. 3.8) and loose fills (Fig 3.9, 3.10 and 3.11). For lightweight concretes, the mean deviation of values calculated from linear regression curves in relation to test values upon which the curves are based was 7.0 percent for about 700 tests of 13 types of concrete analyzed. The coefficients of determination (square of correlation coefficient) averaged 0.92. It is probable, therefore, that thermal conductivity calculated from density or from a mathematical model has greater validity in any given case than a single value based upon a small test specimen.

Another purpose of Part I was to provide methods for calculating thermal conductivity values of mortars, concretes, and fired clay materials on the basis of volumetric compositions and thermal conductivities of their constituent phases. These phases are, in concretes and mortars, cement pastes and aggregates; in brick, they are the fired clay components as they have been transformed by pyroprocessing. In all of these materials, an additional component is water in the form of sorbed moisture, which has pronounced effects on thermal conductivity that differ among the various masonry materials. In addressing insulating materials such as granular fills, an additional "material" to be considered is air.

Calculational models for thermal conductivity (and for electrical conductivity and modulus of elasticity as well) are theoretically valid for composite materials when the physical properties of the constituent phases are accurately known. The Maxwell and cubic models (Russell, 1935, and Paul, 1960) apply to two-phase materials consisting of a continuous matrix and suspended particles. The present study considers the cubic model (Fig. 3.12) and its applicability to combinations of materials which can be reduced to two phases. Empirical density-based correlations are poor for so-called "sand-gravel" concretes, because of wide variations in thermal conductivity accompanying small variations in density for rocks comprising sand and gravel. As a result, this study has resorted to calculations based on the cubic model, using the well-defined thermal conductivity-density relationship obtained for the cement paste matrix in Fig. 3.13 and estimated thermal conductivities for normal weight natural aggregates based on mineralogic composition of parent rocks (e.g., as shown in Fig. 3.14). Fig. 3.15 presents a chart for estimating thermal conductivities of normal weight concretes.

Table 3.1 shows the entire range of oven-dry thermal conductivities calculated by the cubic model for concretes and mortars made with such "normal weight" aggregates. Table 3.2 provides oven-dry thermal conductivities for lightweight concretes, mortars and

bricks, obtained from linear regression equations which relate oven-dry densities to thermal conductivities (Fig. 3.1 through 3.8 and Table 3.3). The accuracy of the cubic model for estimating thermal conductivities of sanded lightweight aggregate concretes, and of expanded clay and shale fills, is shown in Figures 3.16 and 3.17. Thermal conductivity-density relationships are shown in Fig. 3.14 for calcitic and dolomitic limestones and marble, and quartzitic rocks.

To obtain "practical" thermal conductivity values for various exposure conditions, the oven-dry values of Tables 3.1 and 3.2 were multiplied by appropriate moisture factors (Table 3.4). Table 3.5 lists these suggested "practical" thermal conductivity values for normal weight and lightweight concretes, solid clay bricks, and for cement mortars. The moisture factors of Table 3.4 are based on numerous tests, mostly European, of materials containing various quantities of moisture. Estimated "equilibrium" moisture contents were calculated based on desorption-adsorption curves of moisture content versus relative humidity (Tables 3.6 through 3.9). These equilibrium moisture contents were in turn used to provide moisture factors.

Tables 3.10 through 3.14 list thermal conductivity moisture factors expressed as an increase in thermal conductivity for each one percent of moisture, by weight, based on dry density. Figure 3.18 shows sorbed moisture contents for neat cement pastes and mortars. Figure 3.19 shows sorbed moisture contents for clay bricks, and for pyroprocessed, by-product and natural lightweight aggregates. Figure 3.20 shows the sorbed moisture content for block lightweight concretes for relative humidities of 10 to 80 percent. It is seen that the predominant portion of hygrometric moisture is taken up by the portland cement paste constituent of concrete, and is quite small for bricks and lightweight aggregates.

3.4 PART II - MANUAL CALCULATION METHODS

Thermal conductivity data developed and presented in Part I of the IMI report was used to calculate C-values and U-values of walls ranging in complexity from these consisting simply of monolithic concrete or of solid units and mortar, to those consisting of one or more wythes of hollow or multicored masonry units, with cores empty or filled with insulation. An equation analogous to that for calculating the electrical resistance of circuits with parallel and series components was used to calculate the thermal resistance of each layer in a wall perpendicular to the direction of heat flow and taking the sum of R-values of all layers to obtain the total R value of the wall.

Sample calculations were provided for walls of various types including those with units of multicore and preinsulated types.

Various methods have been used for calculating the thermal transmittance (U-value) of masonry walls built with hollow units. The ASHRAE Handbook of Fundamentals (1985) cites two procedures, termed the "series" and "series-parallel" or "isothermal planes" methods. A regular two-core "stretcher" or flanged-end block with nominal thickness, height, and length of 8 by 8 by 16 in. (0.203 by 0.203 by

0.406 m) may be used for illustration. A representative wall area module is 128 in.^{2} (0.082 m^2) and includes one-half of the face area of the mortar joints.

3.4.1 The Parallel Method

Fig. 3.21 and Table 3.15 are is used for illustration for a wall with cores empty or completely filled with insulation. Using the parallel method, the module is cut into slices with sides perpendicular to the plane of the wall. There are three kinds of slices:

(a) Solid concrete webs, considered to extend through a wall, air-to-air or surface-to-surface

(b) Face shell and core (or face shell and insulation) slices, also extending through the wall. The face shell and core slice is considered to be two slabs of concrete with an air-space (or insulation) between the slabs;

(c) The mortar joint, which is considered to be two "slabs" of mortar with an air-space (or insulation) between them.

The thermal transmittance or thermal conductance is calculated for each slice. The average thermal transmittance or thermal conductance is obtained in two steps. First, the thermal transmittance (or thermal conductance) of each slice is multiplied by its fractional wall face area: the ratio (wall face area of slice)/(total wall face area). Next, the products obtained in step 1 are added. For the unit illustrated, the fractional wall face areas are:

Mortar and air space	0.070
Webs	0.205
Face shell and cores	0.725

TABLE 3.15 DIMENSIONAL DATA FOR 8- BY 16-IN. (200- BY 400-MM) TWO-CORE "REGULAR" CONCRETE UNITS TO BE USED IN CALCULATING U-VALUES OF WALLS WITH FACE SHELL MORTAR BEDDING

Actual Thickness*		Average Thickness of Layers: Face Shells-Mortar (x 2)		Webs-Cores or Webs-Loose Fill		Wall Face-Area Fractions**: Mortar	Face Shells	Webs	Core Space**
in.	(m)	in.	(m)	in.	(m)				
3.62	(0.092)	2.36	(0.060)	1.26	(0.032)	0.07	0.93	0.205	0.795
5.62	(0.143)	2.38	(0.060)	3.24	(0.082)	0.07	0.93	0.205	0.795
7.62	(0.194)	3.04	(0.078)	4.58	(0.116)	0.07	0.93	0.205	0.795
9.62	(0.244)	3.46	(0.088)	6.16	(0.157)	0.07	0.93	0.233	0.767
11.62	(0.295)	3.46	(0.088)	8.16	(0.207)	0.07	0.93	0.251	0.749

* Actual height and length of units are 7.62- by 15.62-in. (0.19- by 0.40 m).
** The sum of face-area fractions in a layer is equal to 1.0.
*** Or loose insulation.

The thermal transmittance or thermal conductance of each slice is the reciprocal of the sum of the thermal resistances of the individual layers which constitute the slice. Since the heat flow is assumed to be unidirectional and perpendicular to the face of the wall, the thickness of each layer is also measured in a direction perpendicular to the face of the wall. The resistances are, in each case, the layer thickness divided by its thermal conductivity. Thermal conductivities are taken as 6 Btu/h-ft^2-(F/in), (0.87 W/m-K) for a traditional sanded mortar and 3.47 Btu/h-ft^2-(F/in) (0.5 W/m-K) for a typical expanded shale concrete weighing 84 pcf (1340 k/m^3). For 4.58 in. (0.116 m) thick cores, the thermal resistance is taken as 1.0 h-ft^2-F/Btu (0.176 m^2-K/W) for an effective thermal conductivity of 4.58/1.0 = 4.58 Btu/h-ft^2-(F/in) (0.66 W/m-K). Alternatively, the cores may be considered to be filled with granular insulation such as perlite with an effective thermal conductivity of 0.35 Btu/h-ft^2 - (F/in.), (0.05 W/m-K). Each face shell of the unit shown is 1.52 in. (0.0386 m) thick.

Calculation of <u>surface-to-surface</u> thermal conductances:

Mortar-air-space slice

$$R_{m-sp} = \frac{3.04}{6} + \frac{4.58}{4.58} = 1.51; \quad C_{m-sp} = 0.662$$

Web slices

$$R_w = \frac{7.62}{3.47} = 2.20; \quad C_w = 0.455$$

Face shell-core slices

$R_{fc} = \frac{3.04}{3.47} + \frac{4.58}{4.58} = 1.88; \qquad C_{fc} = 0.532$

Thermal conductances for each slice are then multiplied by their respective face area fractions; the average thermal conductance is the sum of these products:

(0.662 x 0.07) + (0.455 x 0.205) + (0.532 x 0.725) = 0.525

Average thermal resistance is 1/0.525 = 1.905 h-ft^2-F/Btu.

Total thermal resistance, R_T = 1.905 + 0.85 = 2.75;

U = 0.363 Btu/h-ft^2-F (2.06 W/m^2-K).

Note that total thermal resistance, R_T, is the sum of the average thermal resistance plus the value 0.85 h-ft^2-F/Btu (m^2-K/W) for surface thermal resistance, as given by the ASHRAE Handbook of Fundamentals (1985) for winter conditions. For cores filled with insulating fill [Conductivity = 0.35 Btu/h-ft^2-(F/in) or 0.05 W/m-K], the thermal resistance of cores is obtained as 4.58/0.35 = 13.086. The fractional thermal conductances (i.e., the products of thermal conductances and face area fractions) of the respective slices become:

R_{m-sp} = 13.592; C_{m-sp} = 0.0736 x 0.07 = 0.00515

R_w = 2.20; C_w = 0.455 x 0.205 = 0.0933

R_{fc} = 13.962; C_{fc} = 0.716 x 0.725 = 0.0519

The average thermal resistance is:

1/(0.00515 + 0.0933 + 0.0519) = 6.65; C = 0.150

R_T = 6.65 + 0.85 = 7.50; U = 1/7.50 = 0.133 Btu/h-ft^2-F (0.758 W/m^2-K).

Calculation of <u>air-to-air</u> thermal transmittance:

When the parallel method is based on averaging the thermal transmittance of the individual slices, the value 0.85 h-ft^2-F/Btu (0.15m^2-K/W) for surface resistances is added to the thermal resistances for each slice and the individual thermal transmittances are, for cores empty:

R_{m-sp} = 1.51 + 0.85 = 2.36; U_{m-sp} = 0.424

R_w = 2.20 + 0.85 = 3.05; U_w = 0.328

R_{fc} = 1.88 + 0.85 = 2.73; U_{fc} = 0.366

Average thermal transmittance:

U = (0.07 x 0.424) + (0.205 x 0.328) + (0.725 x 0.366)

U = 0.362 Btu/h-ft^2-F (2.06 W/m^2-K).

For cores filled with insulation [Conductivity = 0.35 Btu/h-ft^2-(F/in) (0.05 W/m^2-K)]:

U = 0.126 Btu/h-ft^2-F (0.716 W/m^2-K).

The parallel method based on calculation of air-to-air thermal transmittances for each slice (i.e. the sum of fractional U-values proportioned according to wall face area fractions of individual slices) yielded an average U-value virtually identical to that based on the calculation of surface-to-surface thermal conductances for each slice for the wall cores empty. For the wall with cores insulated, calculation by proportionate conductances yielded a U-value about six percent higher than that provided by proportionate U-value calculations.

The calculation by the parallel (U) method assumes that there is no lateral heat flow in any layer of material perpendicular to heat flow in a wall. Calculation by the parallel (U) method always provides the lowest U-value for the masonry unit.

The calculation by the parallel (C) method assumes that there is no lateral heat flow except at outer surface-air boundaries. The assumption that these surfaces are isothermal planes is correct, and has been demonstrated in reports of tests of masonry walls in which surface temperatures were listed (e.g. Pennsylvania State University tests).

3.4.2 The Isothermal Planes Method

The isothermal planes calculation method (series-parallel method) yields the highest U-values. This method assumes that heat can flow laterally in layers perpendicular to heat flow that are bounded by isothermal planes. The hollow block previously considered is divided into three layers: two are formed by parallel combinations of face shells and mortar and the middle layer is a parallel combination of webs and cores or webs and insulation. Thermal resistance is calculated for each layer by the equation:

$$R = \frac{R_1 R_2}{a_1 R_2 + a_2 R_1}$$

where a_1 and a_2 are face area fractions of parallel segments in a layer and R_1 and R_2 are respective resistances of these segments. For the hollow block wall of Fig 3.21, the thermal resistance of the face

shell mortar layers is:

$$R_{f,m} = \frac{R_f R_m}{a_f R_m + a_m R_f}$$

in which a_f is the face shell area fraction, equal to 0.93, and a_m is the mortar area fraction, 0.07:

$$a_f = (7.62 \times 15.63)/128 = 0.93$$

$$a_m = 1 - a_f = 0.07$$

Since the thickness of the face shell and mortar layers is 1.52 x 2 inches, then:

$$R_f = 3.04/3.47 = 0.876 \quad h\text{-}ft^2\text{-}F/Btu$$
$$R_m = 3.04/6 = 0.507 \quad h\text{-}ft^2\text{-}F/Btu$$

The thermal resistance of two face shell and mortar layers is:

$$R_{f,m} = \frac{0.876 \times 0.507}{(0.93 \times 0.507) + (0.07 \times 0.876)}$$

$$R_{f,m} = 0.834 \ h\text{-}ft^2\text{-}F/Btu \ (0.147 \ m^2\text{-}K/W).$$

Thickness of the web and core layer is 4.58 in.; the thermal resistances of parallel segments in this layer are:

$$R_w = 4.58/3.47 = 1.320 \ h\text{-}ft^2\text{-}F/Btu$$

$$R_c = 4.58/4.58 = 1.0 \ h\text{-}ft^2\text{-}F/Btu$$

$$(\text{or} \quad R_{ins} = 4.58/0.35 = 13.09 \ h\text{-}ft^2\text{-}F/Btu)$$

Face area fractions are 0.205 for webs and 1 - 0.205 = 0.795 for cores. The thermal resistance of the web and core layer is:

$$R_{w,c} = \frac{1.32 \times 1.0}{(0.205 \times 1.0) + (0.795 \times 1.32)}$$

$$R_{w,c} = 1.052 \ h\text{-}ft^2\text{-}F/Btu \ (0.185 \ m^2\text{-}K/W).$$

The total thermal resistance of the block is obtained by adding the thermal resistances of the various layers to the surface thermal resistance of the two air films, 0.85:

$$R_T = 0.834 + 1.052 + 0.85 = 2.737$$

$$h\text{-}ft^2\text{-}F/Btu \ (0.482 \ m^2\text{-}K/W)$$

$$U = 1/R_T = 1/2.737 = 0.365 \ Btu/h\text{-}ft^2\text{-}F, \ (2.07 \ W/m^2\text{-}K).$$

The thermal resistance of the middle layer for cores filled with granular insulation [conductivity = 0.35 Btu/h-ft^2-(F/in) (0.05 W/m^2-K), is recalculated. The thermal resistance of the insulated cores is 4.58/0.35 = 13.69. The thermal resistance of the web and insulated core layer, $R_{w,ins}$, is:

$$R_{w,ins} = \frac{1.32 \times 13.09}{(0.205 \times 13.09) + (0.795 \times 1.32)}$$

$$= 4.629 \text{ h-ft}^2\text{-F/Btu } (0.815 \text{ m}^2\text{-K/W})$$

$$R_T = 0.834 + 4.629 + 0.85 = 6.313 \text{ h-ft}^2\text{-F/Btu}$$

$$(1.111 \text{ m}^2\text{-K/W})$$

$$U = 1/R_T = 1/6.313 = 0.158 \text{ Btu/h-ft}^2\text{-F}$$

$$(0.90 \text{ W/m}^2\text{-K}).$$

3.4.3 Comparison of the Three Calculation Methods

Calculation methods are compared in Table 3.16 for walls of regular 8 in. thick hollow-core blocks, with moisture adjusted thermal conductivity of concrete of 3.47 Btu/h-ft^2-(F/in) (0.5 W/m-K). U-values for CMU_s made of materials with different thermal conductivities will vary from those shown here.

TABLE 3.16 CALCULATED U-VALUE OF CONCRETE MASONRY BLOCKS

CALCULATION METHOD	Cores Empty	Cores Insulated
	Btu/h-ft^2-F (W/m^2-K)	
PARALLEL (C)	0.363 (0.206)	0.133 (0.758)
PARALLEL (U)	0.362 (0.206)	0.126 (0.716)
SERIES-PARALLEL	0.365 (0.207)	0.158 (0.900)

Both versions of the parallel method underestimate U-values and are considered unacceptable for walls of hollow blocks with in situ applied insulation, premolded insulating inserts, or for walls of multicore units.

The British CIBS Guide (1980) recommends calculation of resistance of <u>hollow blocks</u> by both parallel (conductance) and series-

parallel methods and taking of the arithmetic mean of R-values obtained by the two methods. The USSR "SNiP" II-3-79 (1986) recommends using the sum of one-third of the parallel (conductance) plus two-thirds of the series-parallel R-values as an estimate of thermal resistance for a wall.

Yarbrough (1985) citing data of Wilson (1984), compared series-parallel calculated R-values for regular two-core lightweight concrete blocks (40 to 60 pcf, (i.e. 647 to 961 kg/m^3) containing low-density granular perlite core insulation, with R-values calculated using a computer program based on finite difference analyses, "HEATING 5." The mean difference between R-values for ten pairs of calculations by both methods was less than two percent. The concrete-insulation thermal conductivity ratio ranged from 4.4 to 11.3. See Appendix C for a more detailed discussion of this work.

While parallel and series-parallel resistance calculations yield upper and lower bounds, values obtained in ASTM C236 guarded hot-box tests have been much closer to series-parallel values. In analyzing data for 172 wall tests of multi-core and large-core uninsulated, in situ-insulated, and pre-insulated blocks, series-parallel calculated U-values deviated from test values by an average of 6.2 percent. The mean bias was +4.9 percent for preinsulated block walls, for which the concrete-insulation conductivity ratio was the highest. For the other large core and multi-core groups the mean bias ranged from +1.7 to -1.6 percent, indicating that calculated values showed a virtual one-to-one correlation with test values for these groups. For preinsulated block walls, the calculated U-values were about five percent higher than the test values.

The foregoing discussion indicates that the series-parallel method provided accurate means for estimating R and U values of hollow masonry walls, irrespective of the complexity of core configurations of masonry units or degree of conductivity mismatch for contiguous materials in parallel arrangements.

3.4.4 Expansion of Series-Parallel Equation for Calculating R-Values of Layers in a Multi-layer Masonry Wall

The simple arrangement of webs, cores, and insulation in Fig. 3.21 involves only two different parallel heat flow paths in calculating the R-value for any layer. When preinsulated or multicore types of blocks are used there may be three or four different "materials" arranged in parallel in some layers. One example would be the unit shown in Fig. 3.21 fitted with premolded insulating insert layers in contact with interior face shell surfaces. The thickness of the core space between the insulation slabs is reduced and there now are five layers instead of three. Furthermore, the insulation layers and the thinner core layer now traverse the common air-space between flanged ends at the vertical joint between adjacent blocks. This air space can be treated as a "material" with an effective thermal

conductivity equal to layer thickness divided by thermal resistance of the space. The effective thermal conductivity of the undivided space is thickness/R_{sp} or (for the unit shown) 4.58/1 = 4.58 Btu/h-ft^2-(F/in), (0.66 W/m-K). (In U.S. units at a mean temperature of 50F (10C) the effective thermal conductivity of the air space is numerically equal to its thickness). Thus, the thermal resistance of the "layer" of air in the insulation layer is its thickness/4.58. In the cores proper, the remaining empty core space is reduced in thickness but is still thick enough to be assigned a resistance value of 1.0 (0.176). Two effective thermal conductivities must therefore be used for core space: one for the cores proper, and another higher value for the uninsulated spaces between ends of adjacent units. The insulation arrangement described is typical of some first generation insulating inserts; the uninsulated end spaces provided thermal bridges when applied to standard blocks of traditional core configurations. The newest generation of preinsulated blocks has largely solved this problem by redesigning the core, web and insert geometry to virtually eliminate uninsulated end space (and mortar joint space) thermal bridges. R values have been increased further by reducing fractional web areas.

For the unit of Fig. 3.21 fitted with first generation insulating inserts there are five layers: two layers with face shell and mortar parallel paths; two layers with three parallel paths each consisting of insulation, webs, and the "partial" air-spaces between ends of units; and the middle layer with four parallel paths consisting of a full air-space (core), webs, partial air-space at ends, and a web of insulating material that holds together the two slabs of insulation in contact with face shells to form a single insert.

The equation used for calculating thermal resistance of layers (isothermal planes) in simple large core hollow unit masonry wall given earlier is:

$$R = \frac{R_1 R_2}{a_1 R_2 + a_2 R_1}$$

in which a_1 and a_2 are face area fractions of parallel segments in a layer [i.e., ratio of (wall face area of a given segment)/(total wall face area)]; and R_1 and R_2 are respective thermal resistances of these segments. This equation is expanded to include any number of parallel heat flow paths in a layer of uniform thickness:

$$R = \frac{R_1 R_2 \ldots R_n}{\frac{a_1 R_1 R_2 \ldots R_n}{R_1} + \frac{a_2 R_1 R_2 \ldots R_n}{R_2} + \ldots \frac{a_n R_1 R_2 \ldots R_n}{R_n}}$$

or:

$$R = \frac{1}{\frac{a_1}{R_1} + \frac{a_2}{R_2} + \ldots \frac{a_n}{R_n}}$$

in which the sum of the area fractions $a_1 + a_2 + \ldots + a_n = 1.0$. R_1, $R_2, \ldots R_n$ are thermal resistances of parallel segments of different materials in a layer bounded by isothermal planes corresponding to area fractions with like subscripts.

This general equation is suitable for calculating the R-values of such multi-layer walls as those consisting of multi-core or preinsulated units. The equation accounts for mortar joints and air-spaces or partial air-spaces in calculations. Please note that while a single thermal resistance value was used for air-spaces in large core unit walls, i.e. 1.0 h-ft^2-F/Btu (0.176 m^2-K/W), higher R-values, as calculated by Anderson (1980), are used in calculations for multi-core unit walls in which the cores are small and are usually closed at top ends by a concrete diaphragm and at bottoms by mortar.

3.4.5 Conclusion

It is concluded that the series-parallel calculation of R and U values of heterogeneous masonry walls, of simple or complex core geometry, provides estimates in satisfactory agreement with test values. Among the calculation procedures appearing in various codes, the USSR SNiP (1979 and 1986) method, which weights parallel (conductance) and series-parallel calculations in a 1 to 2 ratio, respectively, provides estimates of U-values which differ little from series-parallel values. The best estimate probably lies between the series-parallel method and the USSR estimates.

Fig. 3.1

NORTH AMERICAN EXPANDED SLAG CONCRETES

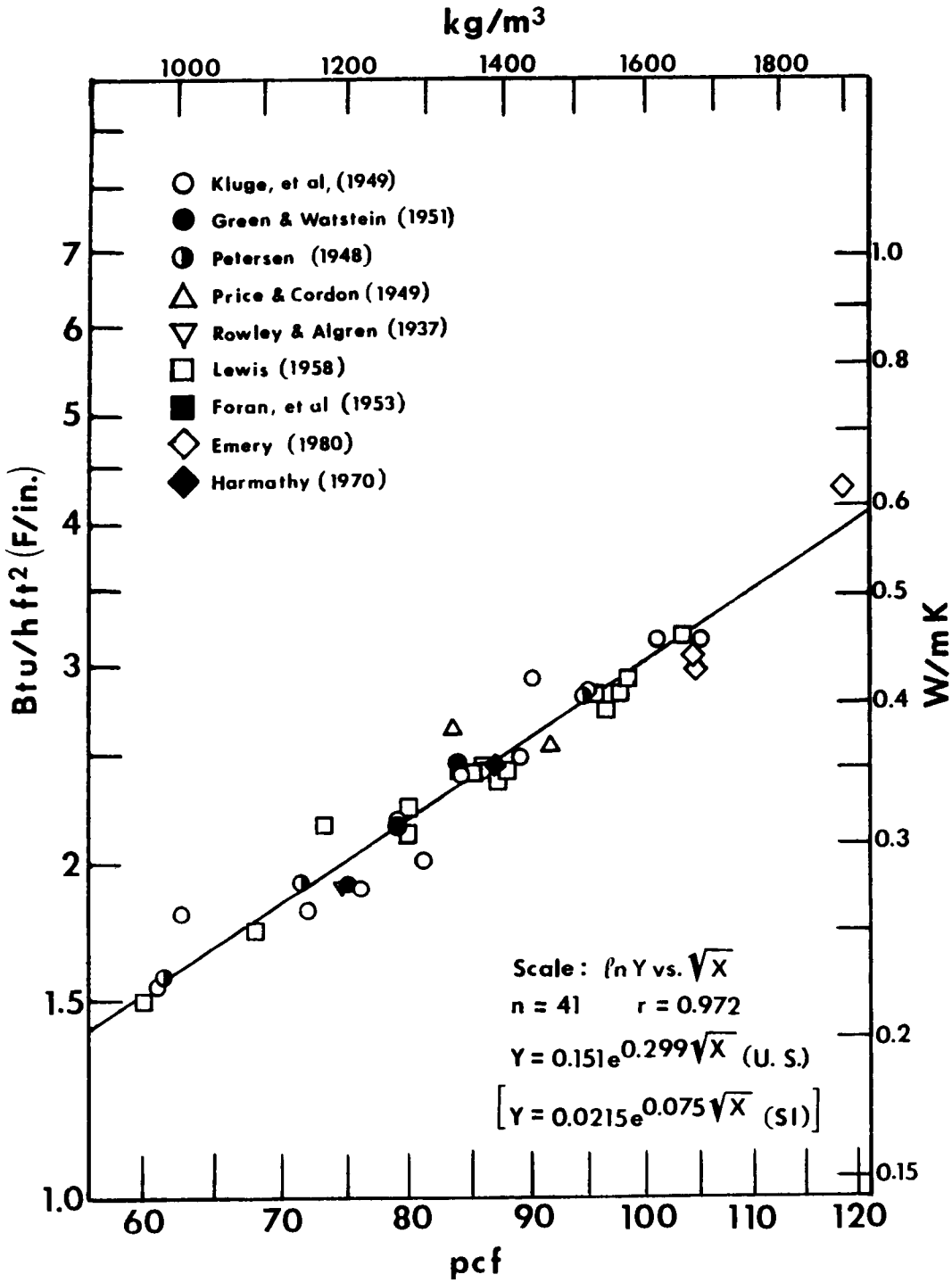

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Fig. 3.2

EUROPEAN EXPANDED SLAG CONCRETES

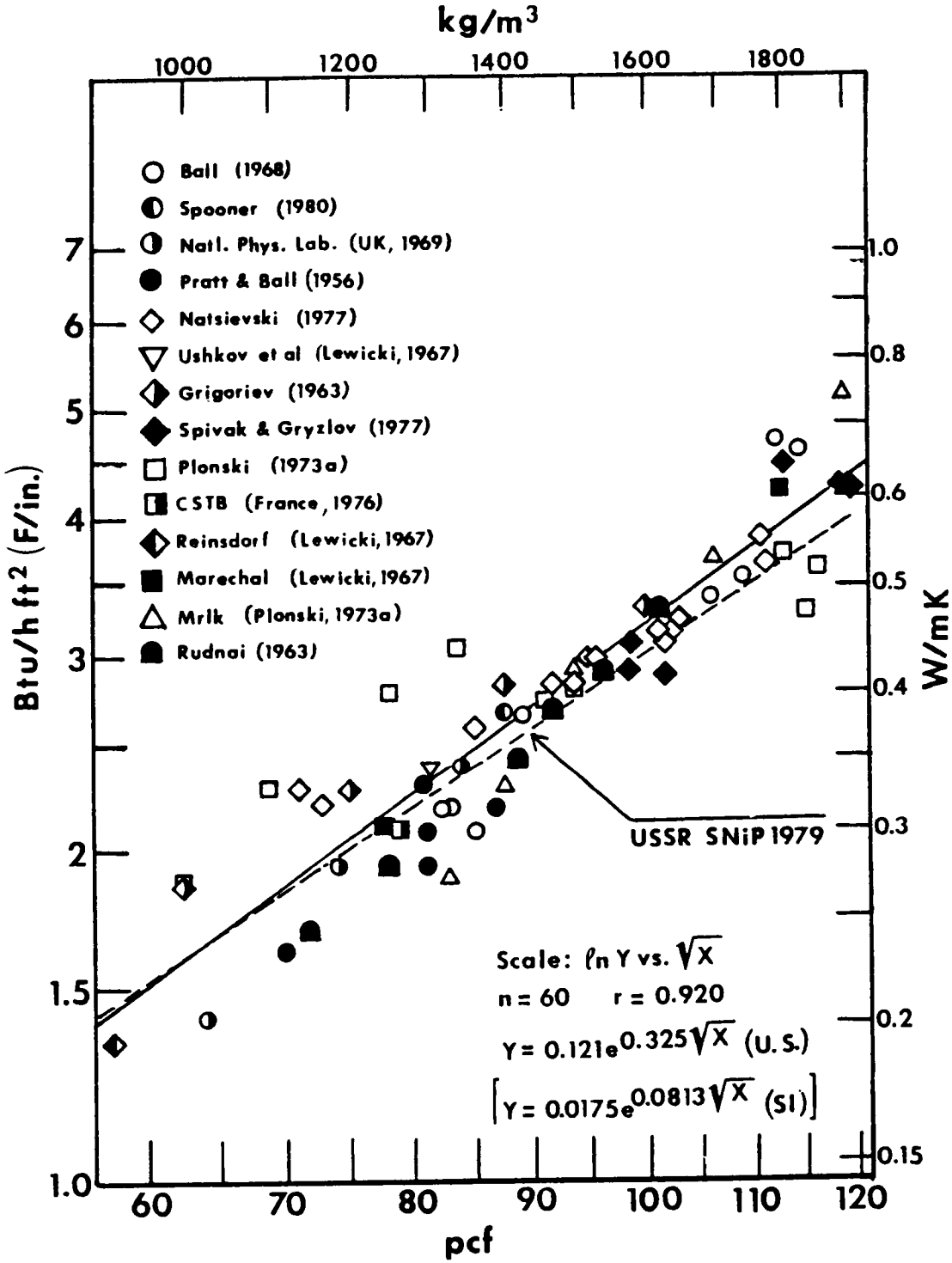

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Fig. 3.3

NORTH AMERICAN EXPANDED CLAY AND SHALE CONCRETES

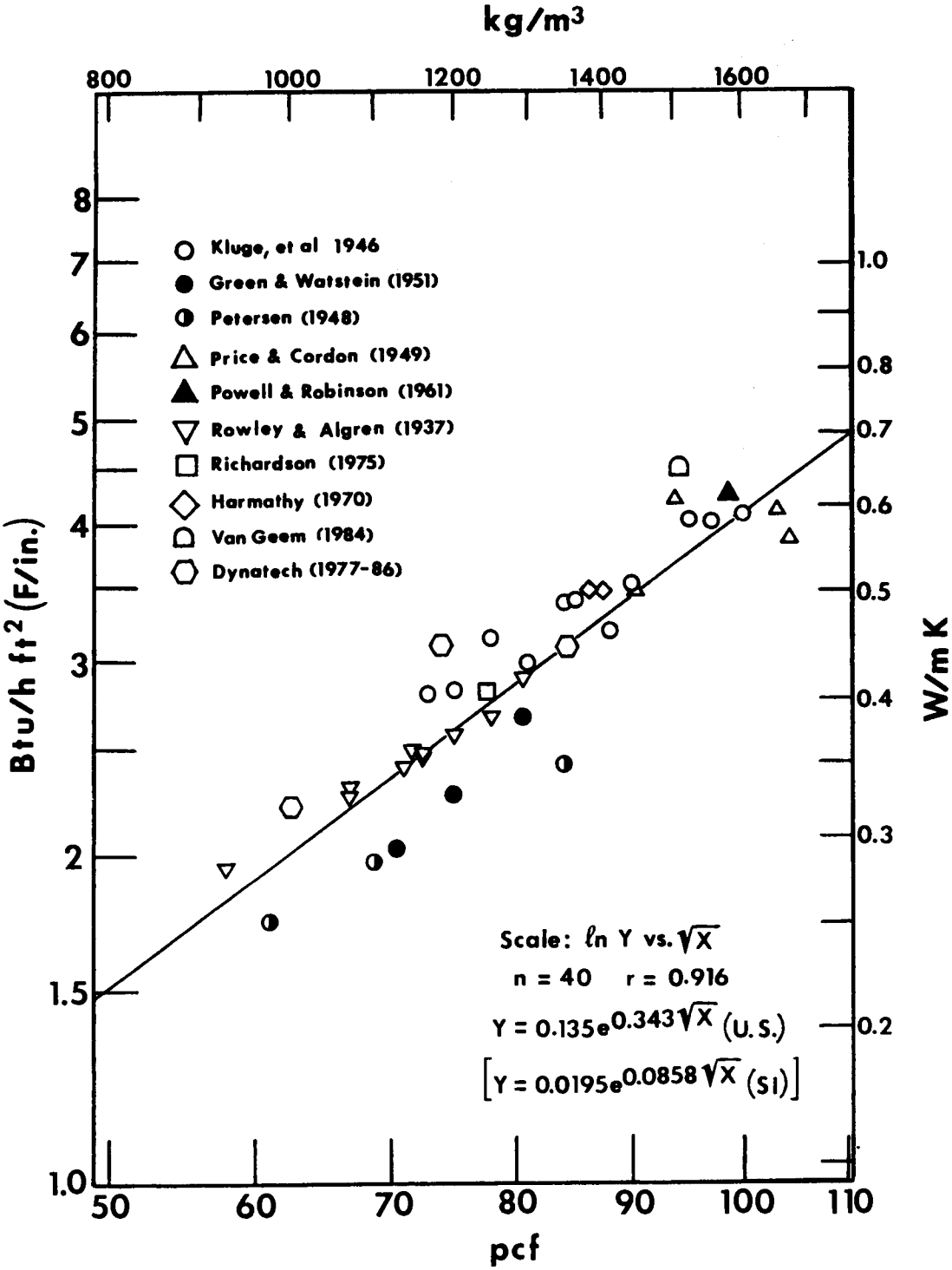

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Fig. 3.4

EUROPEAN SINTERED AND ROTARY KILN EXPANDED CLAY AND SHALE CONCRETES

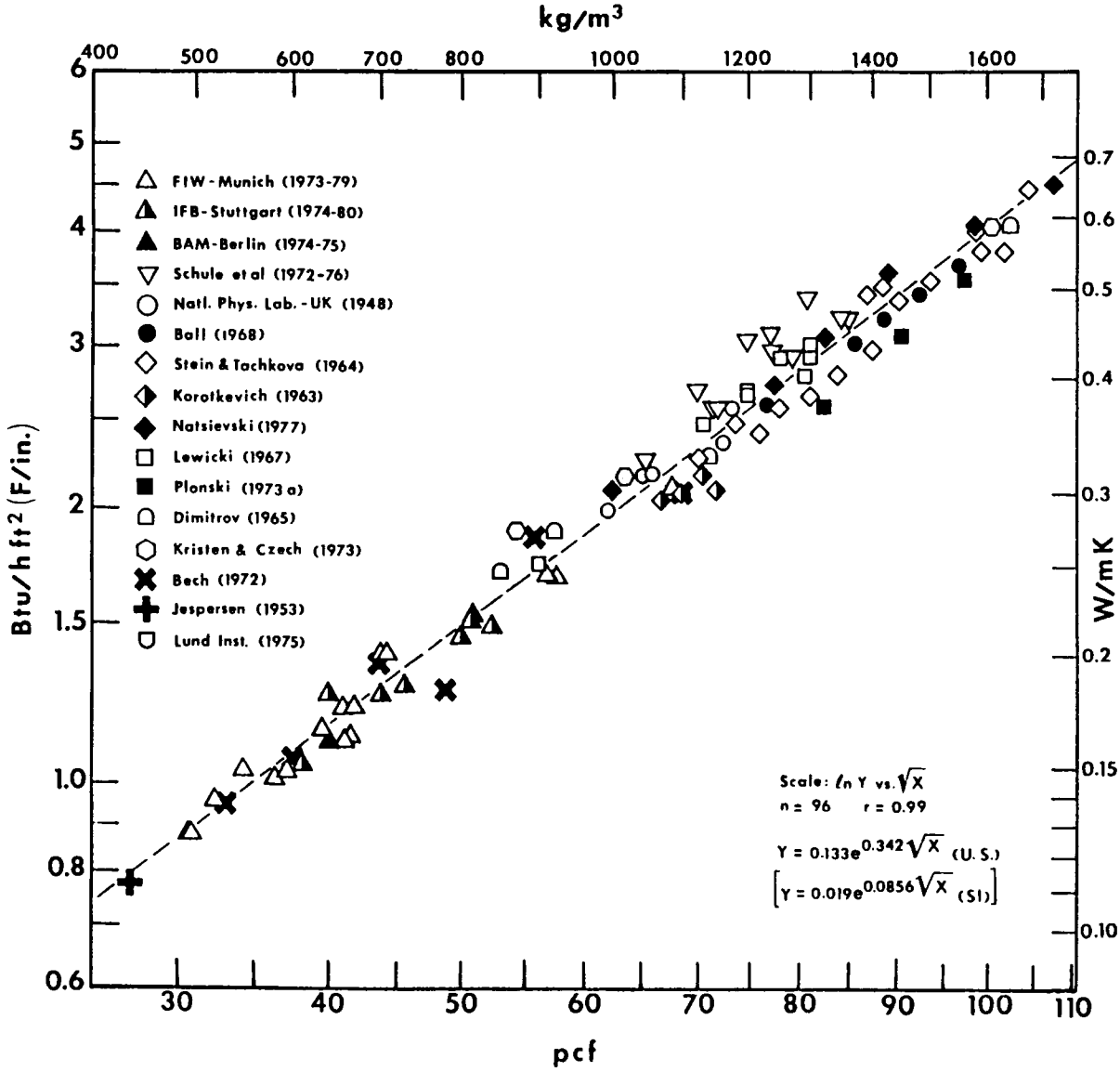

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Fig. 3.5

SANDED ROTARY KILN EXPANDED CLAY AND SHALE CONCRETES

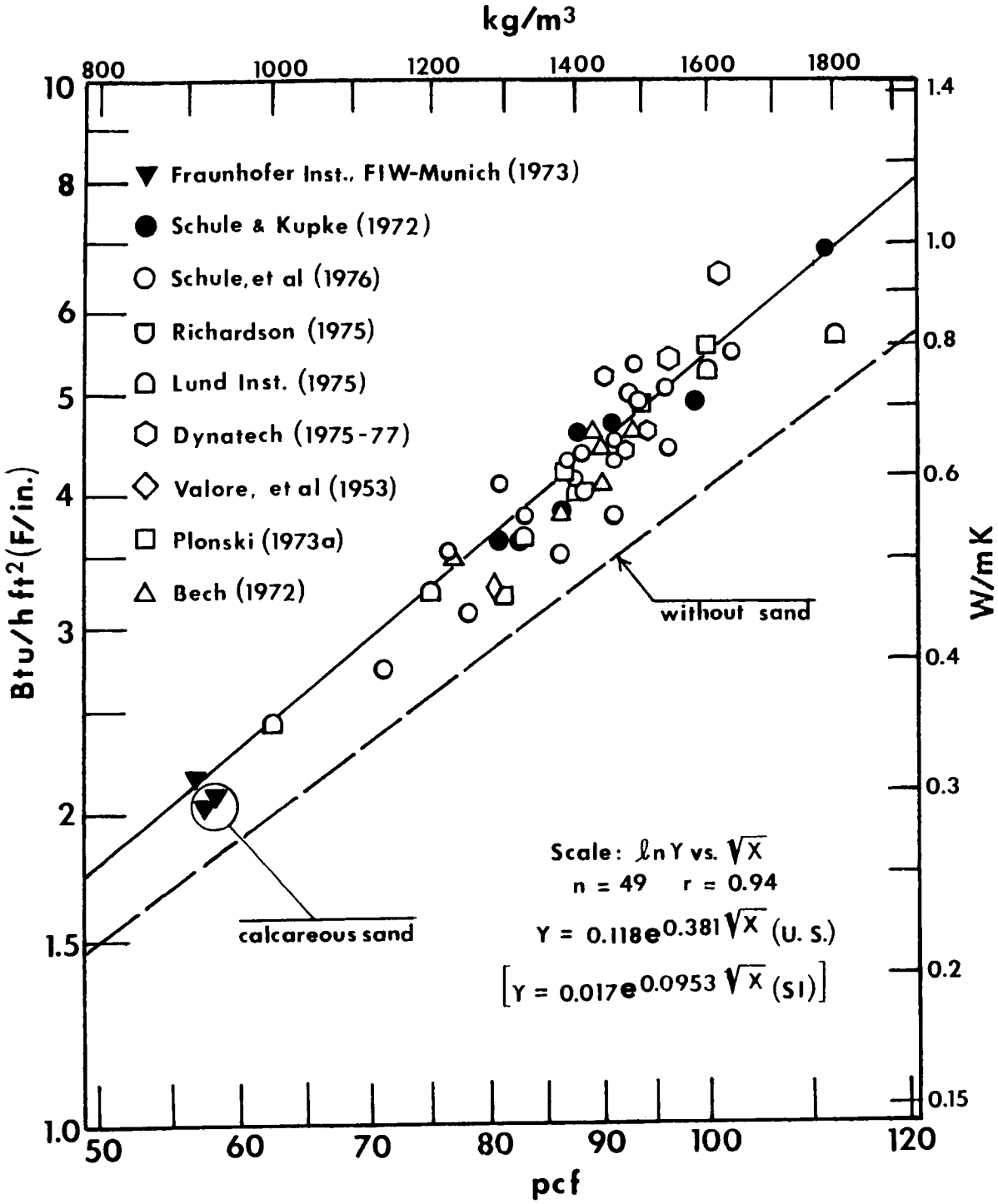

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Fig. 3.6

PERLITE CONCRETES

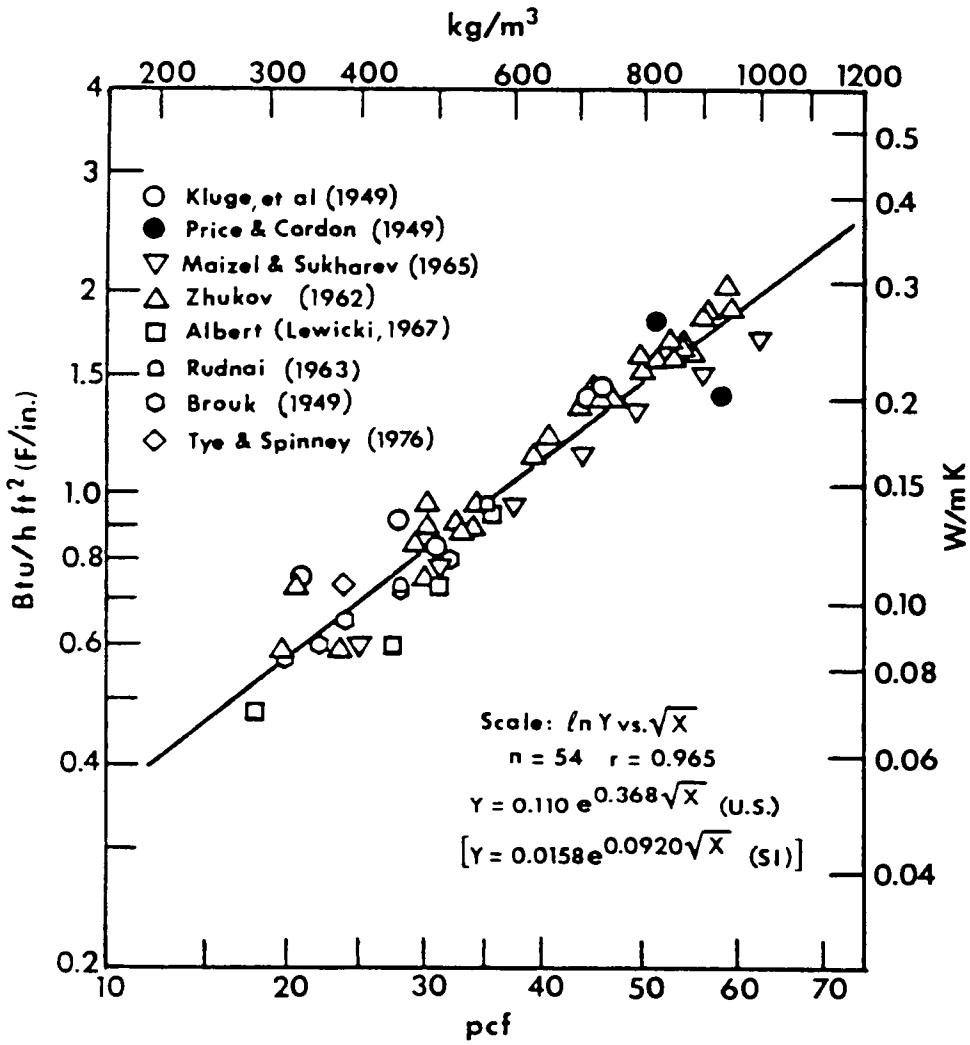

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Fig. 3.7

VERMICULITE CONCRETES

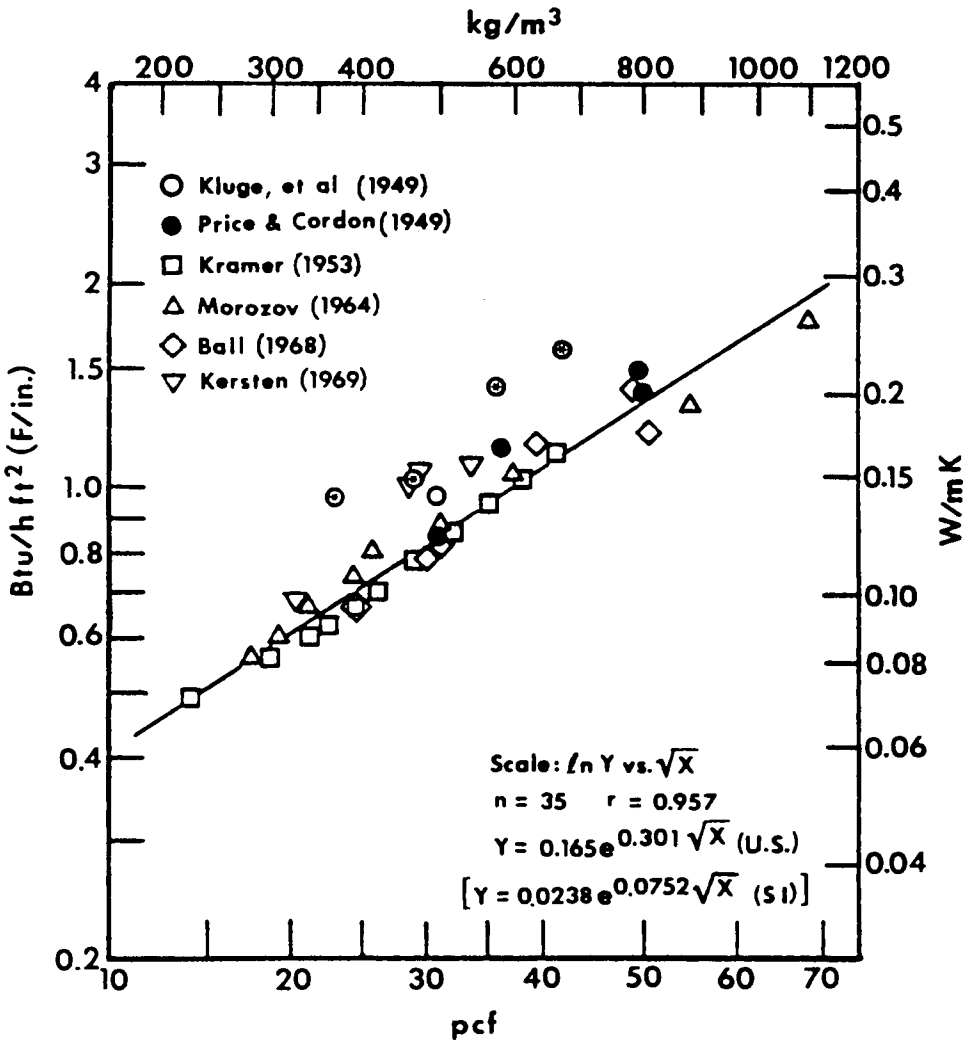

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Fig. 3.8

FIRED CLAY MATERIALS

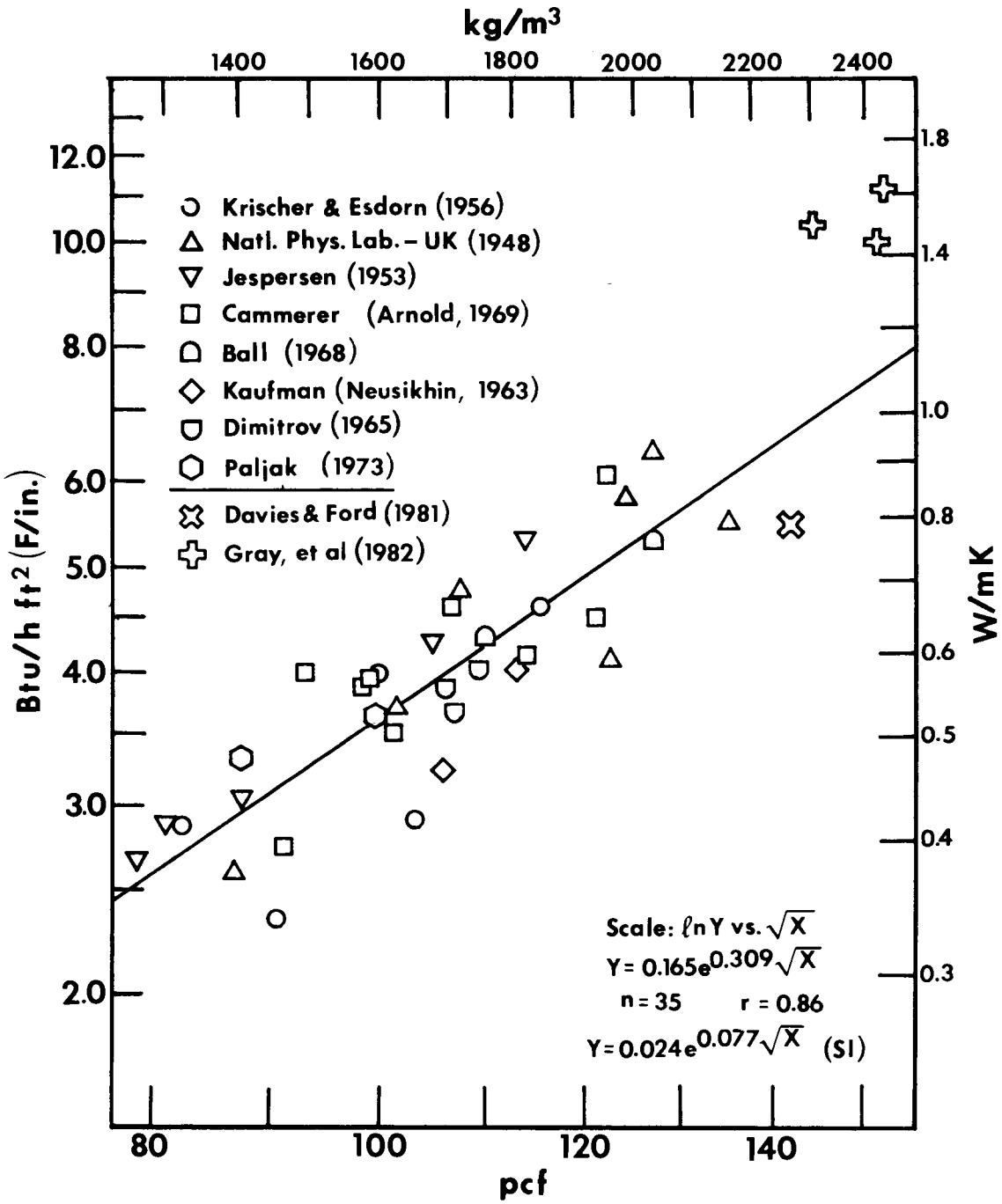

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Fig. 3.9

PERLITE LOOSE FILLS

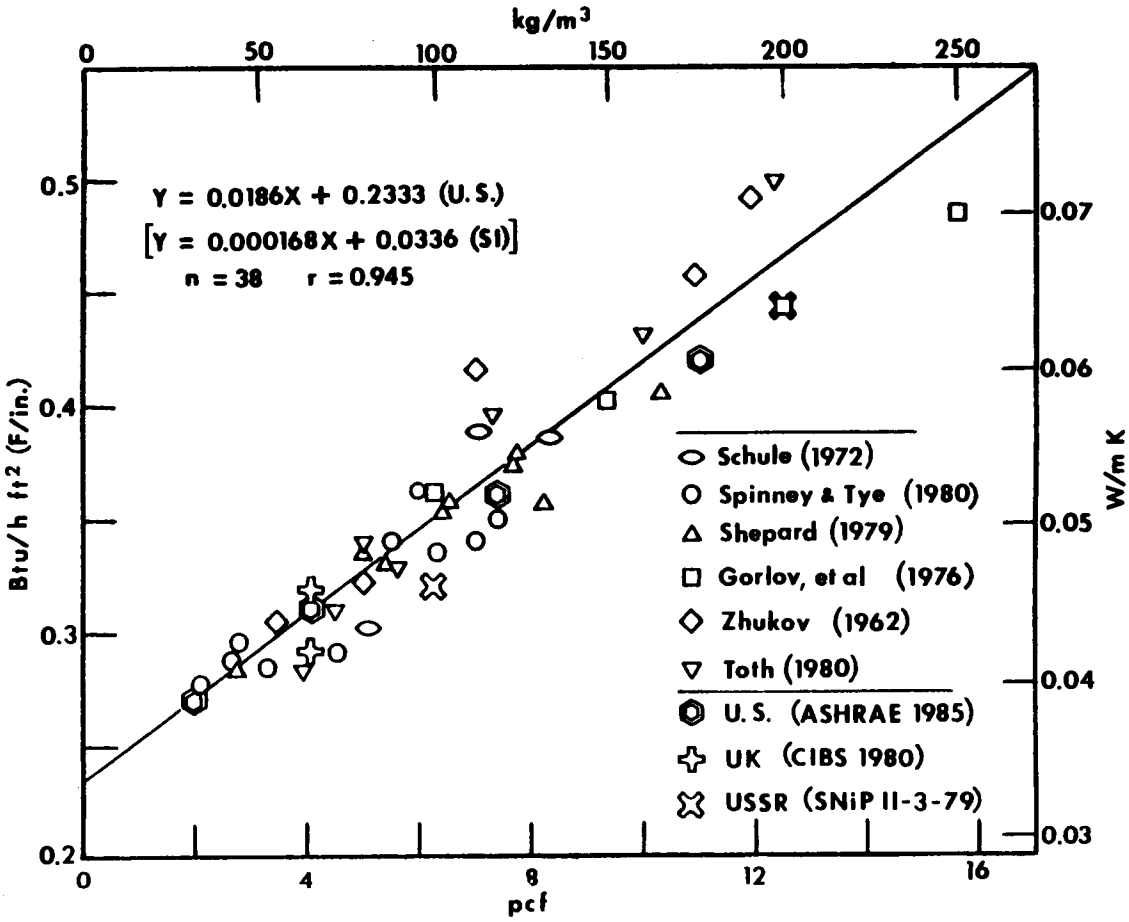

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Fig. 3.10

VERMICULITE LOOSE FILLS

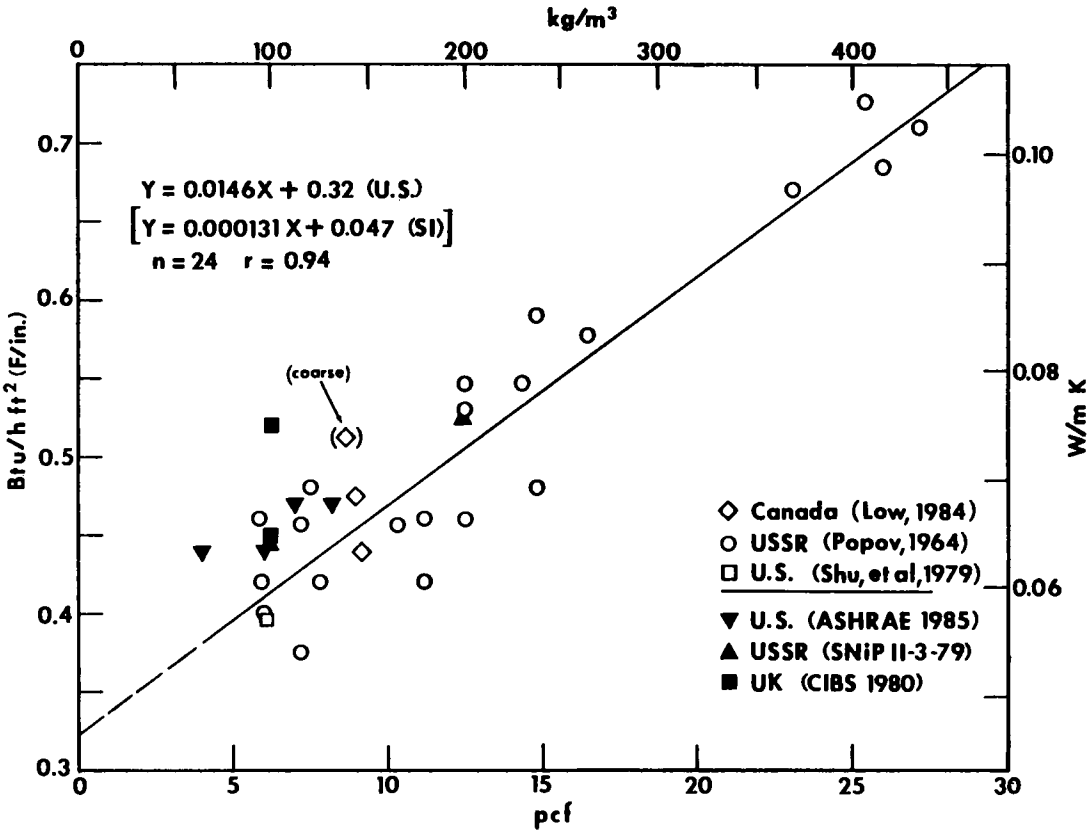

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Fig. 3.11

EXPANDED CLAY AND SHALE LOOSE FILLS

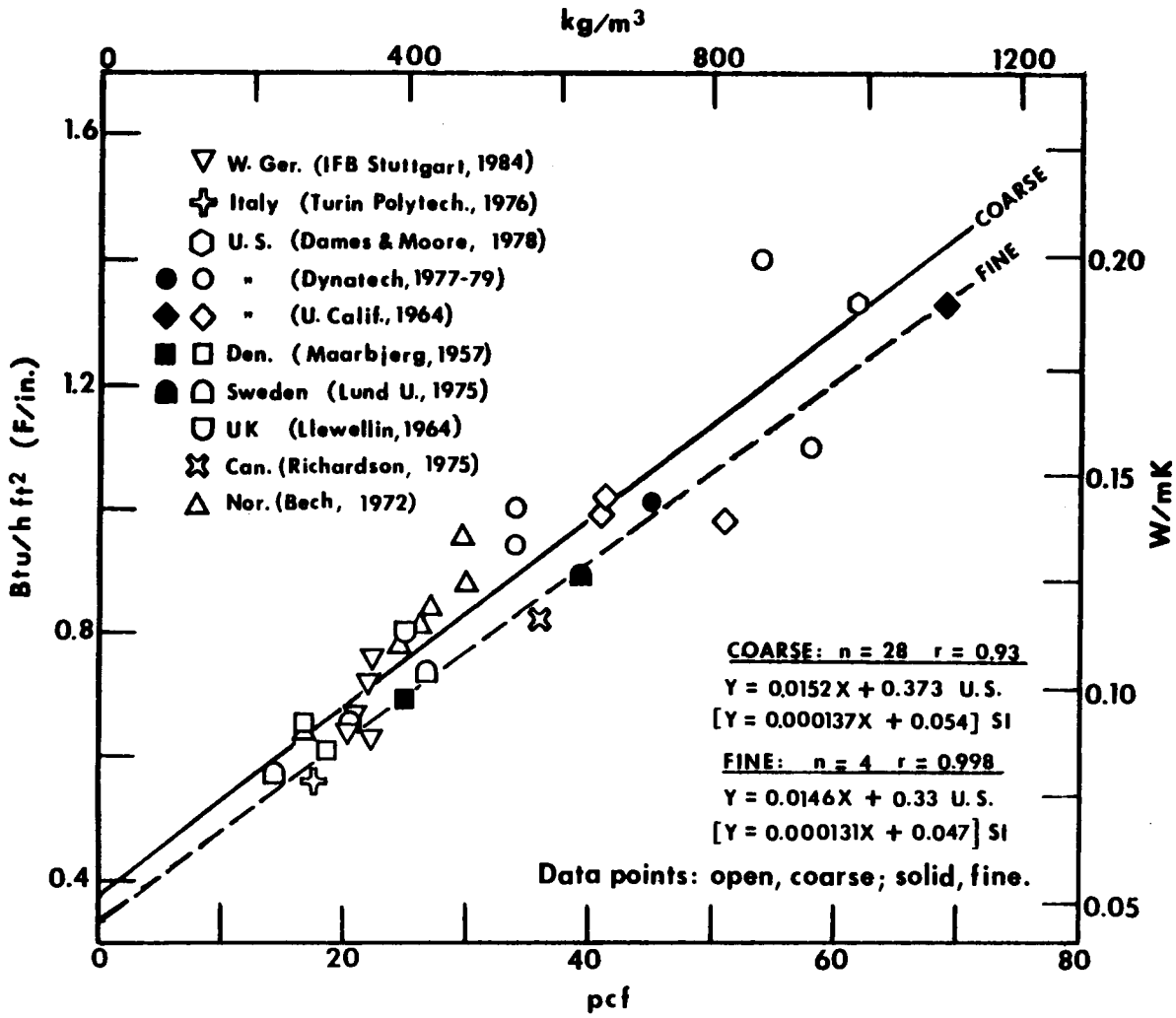

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Fig. 3.12

THE CUBIC MODEL

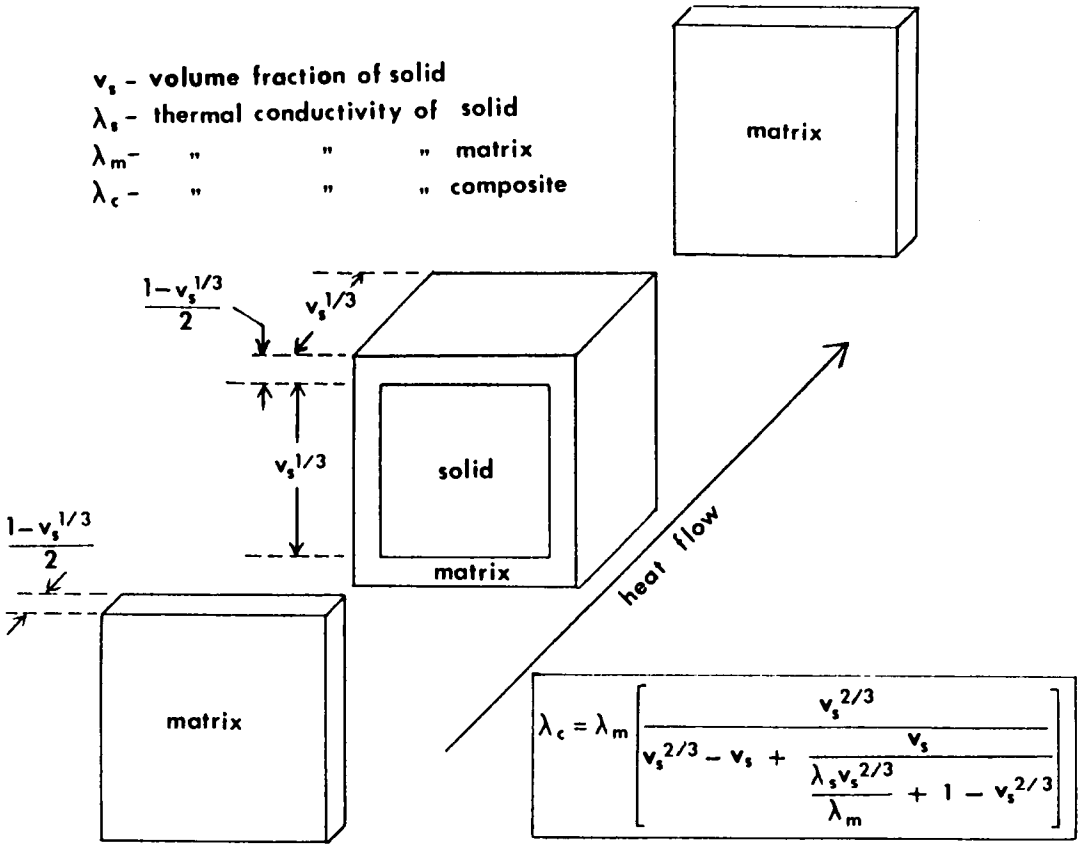

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Fig. 3.13

NEAT CEMENT PASTES AND FOAM CONCRETES

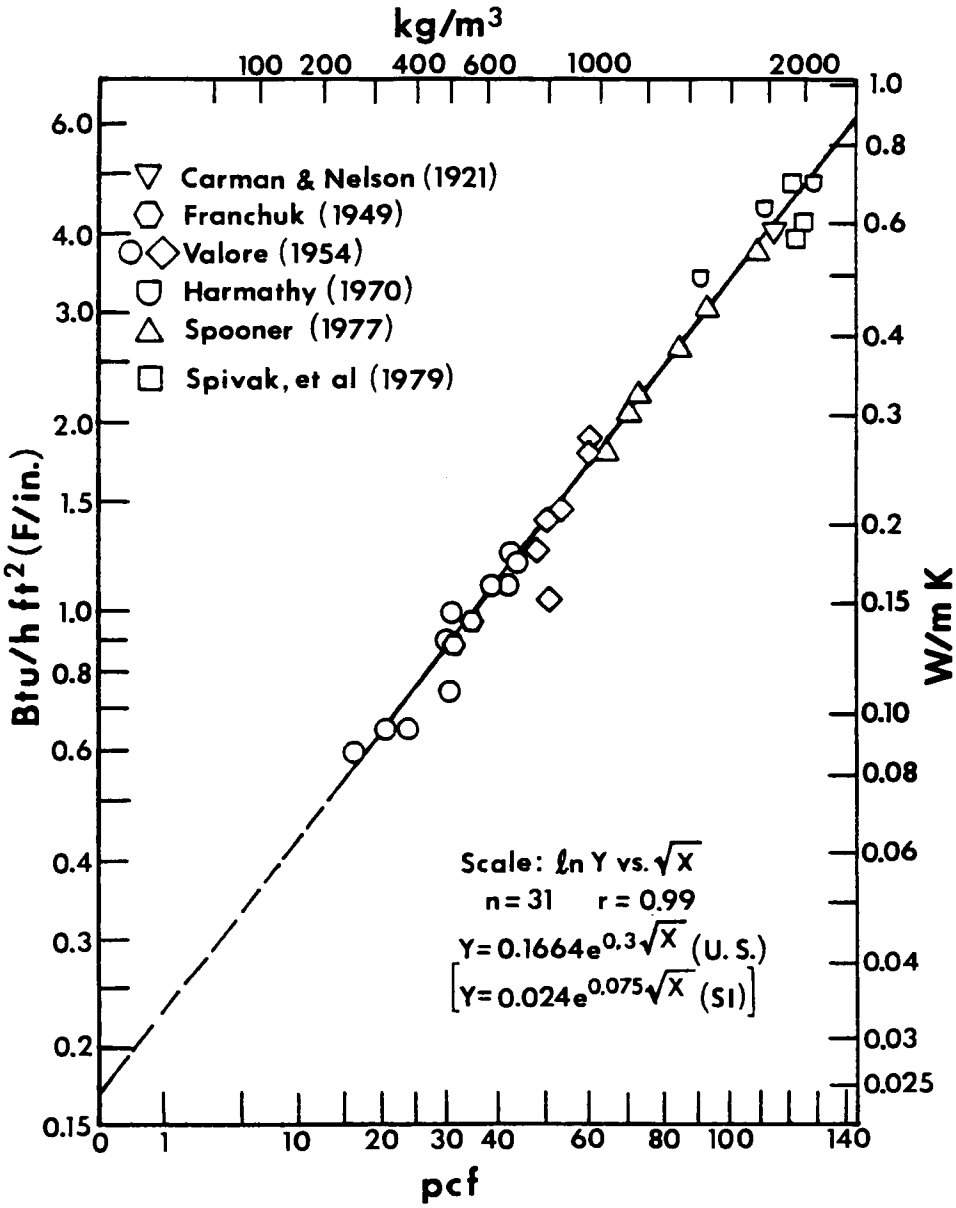

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Fig. 3.14

THERMAL CONDUCTIVITY OF ROCKS BASED ON MINERALOGIC COMPOSITION

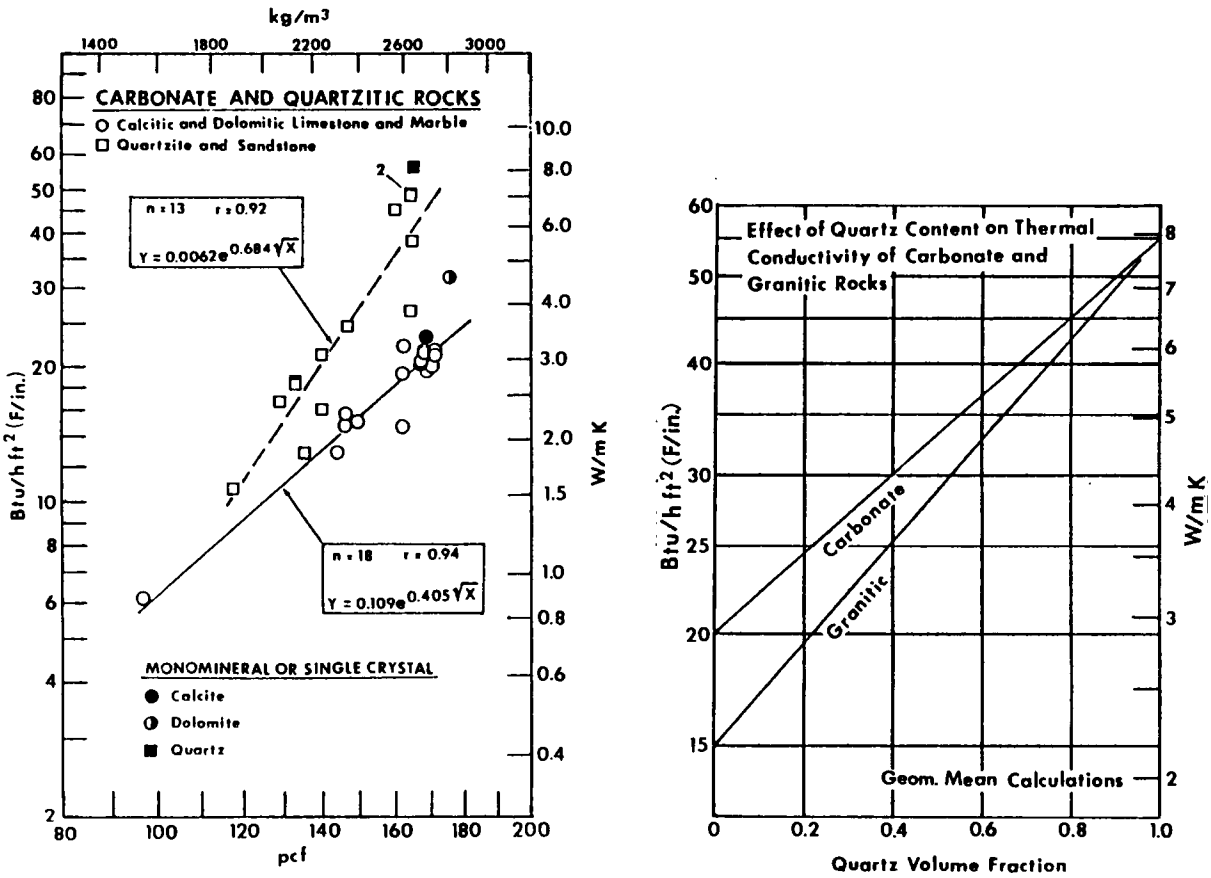

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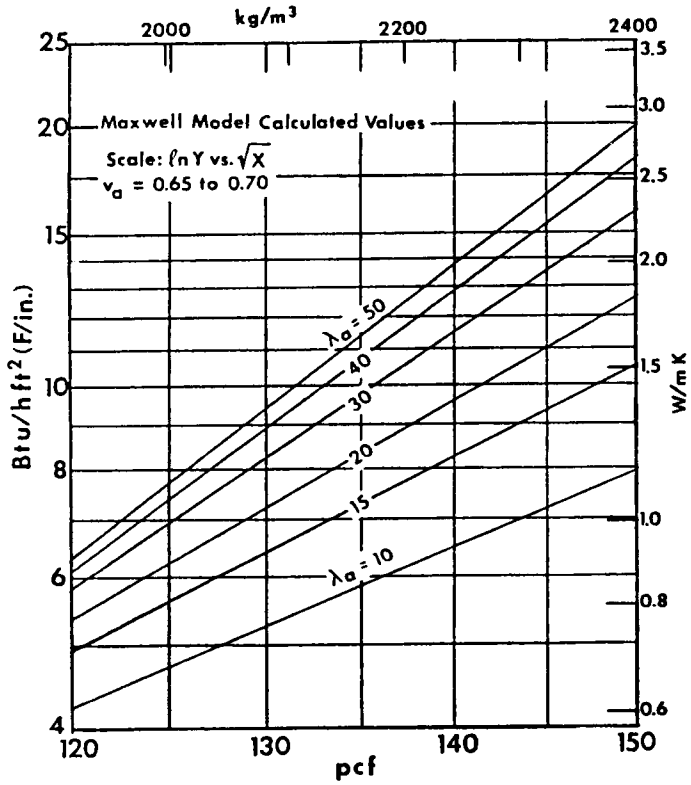
Fig. 3.15

ESTIMATION OF THERMAL CONDUCTIVITIES FOR NORMAL WEIGHT CONCRETES



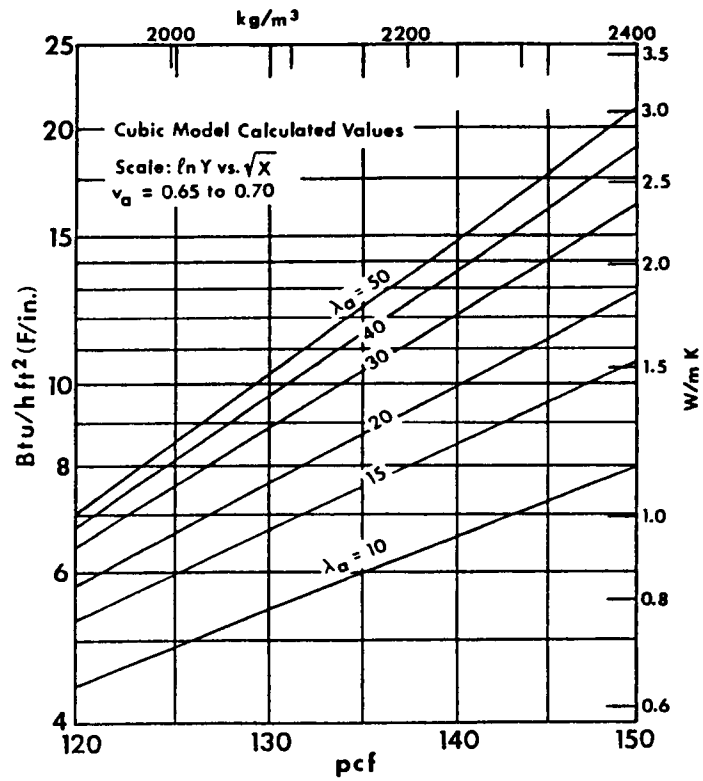


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Fig. 3.16

CORRELATION OF TEST VALUES vs. CUBIC MODEL CALCUALTIONS FOR SANDED AND EXPANDED CLAY AND SHALE CONCRETES

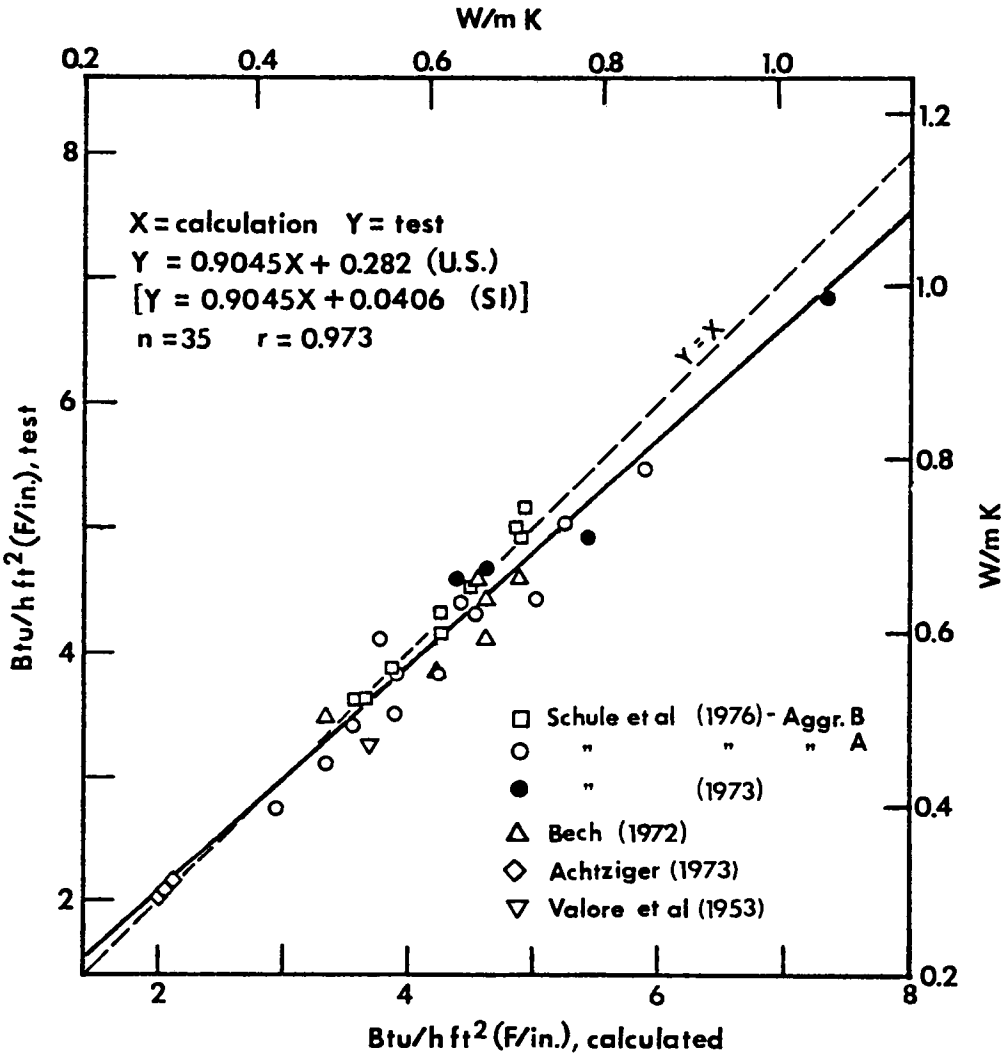

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Fig. 3.17

CORRELATION OF TEST VALUES vs. CUBIC MODEL CALCULATIONS FOR EXPANDED CLAY AND SHALE FILLS

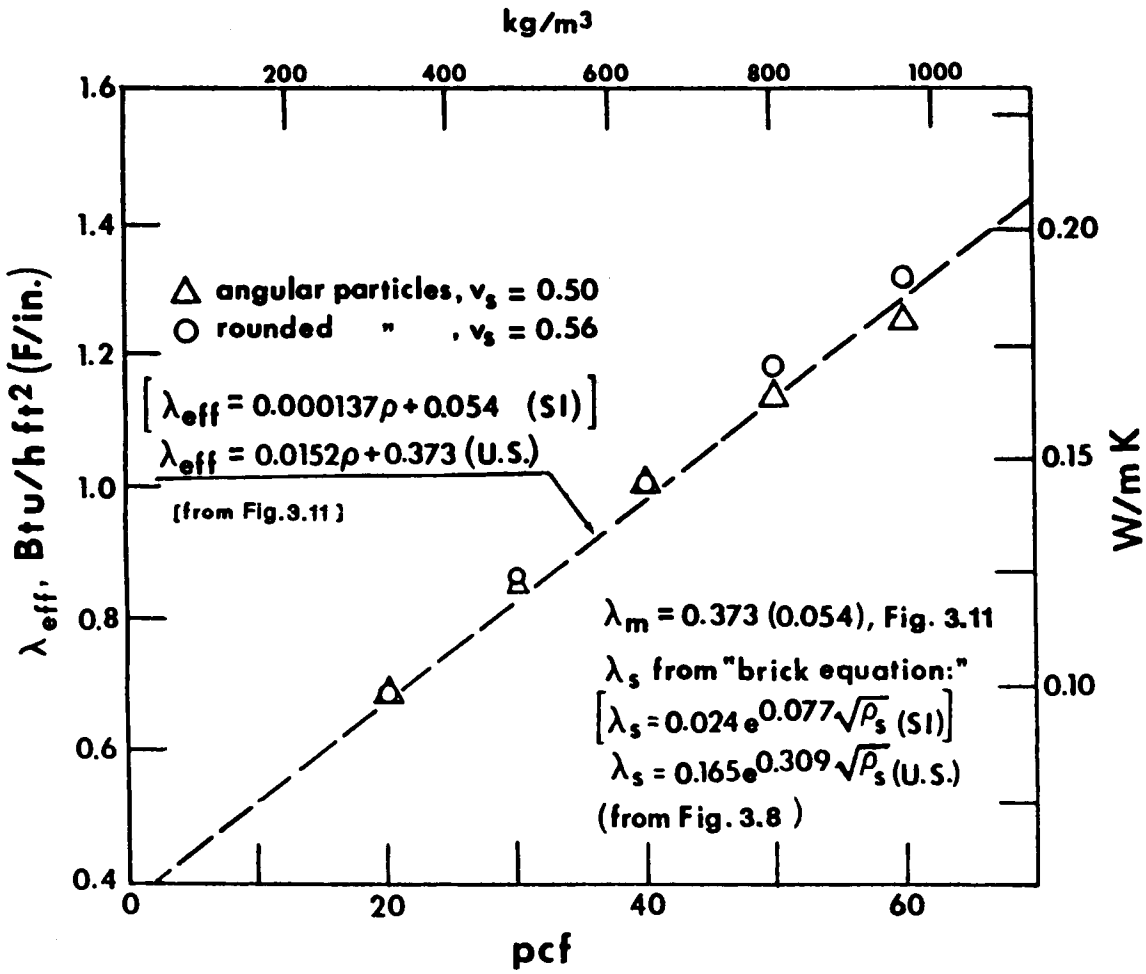

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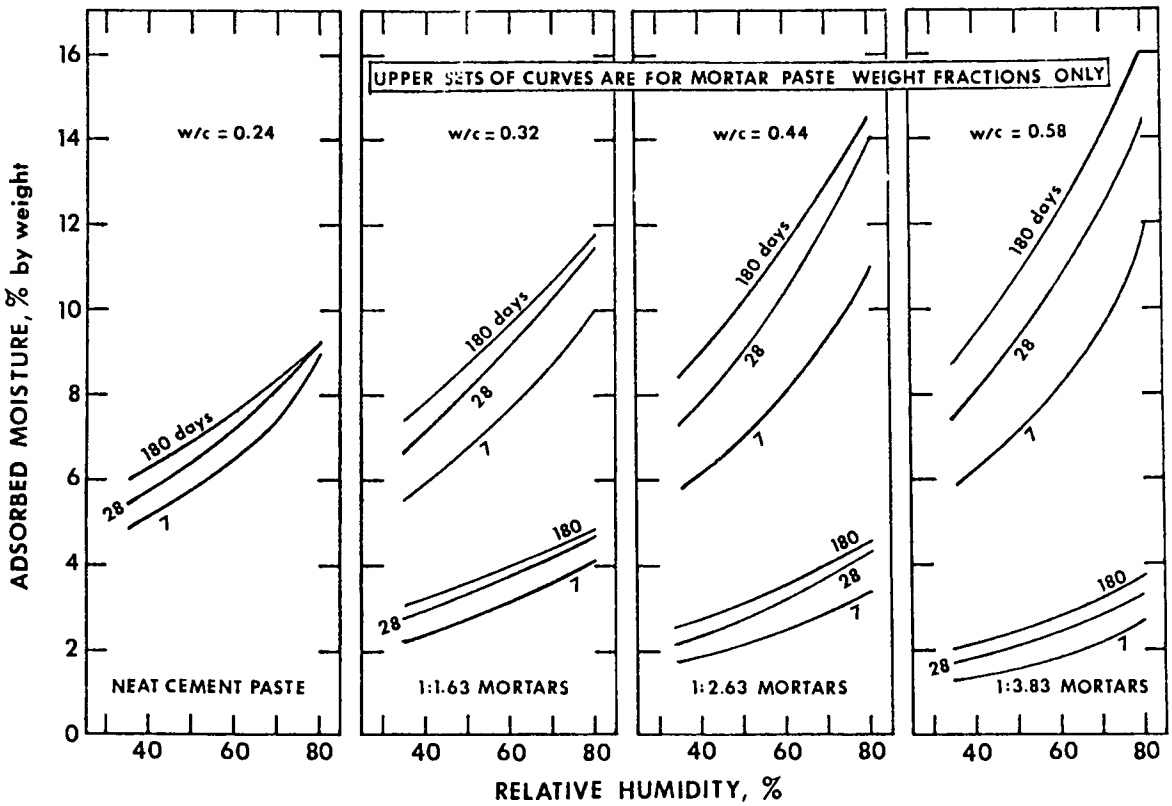
Fig. 3.18

SORBED MOISTURE CONTENTS FOR CEMENT PASTES AND MORTARS



Adapted from Powers & Brownyard (1946)

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Fig. 3.19

SORBED MOISTURE CONTENTS FOR CLAY BRICKS AND FOR AGGREGATES

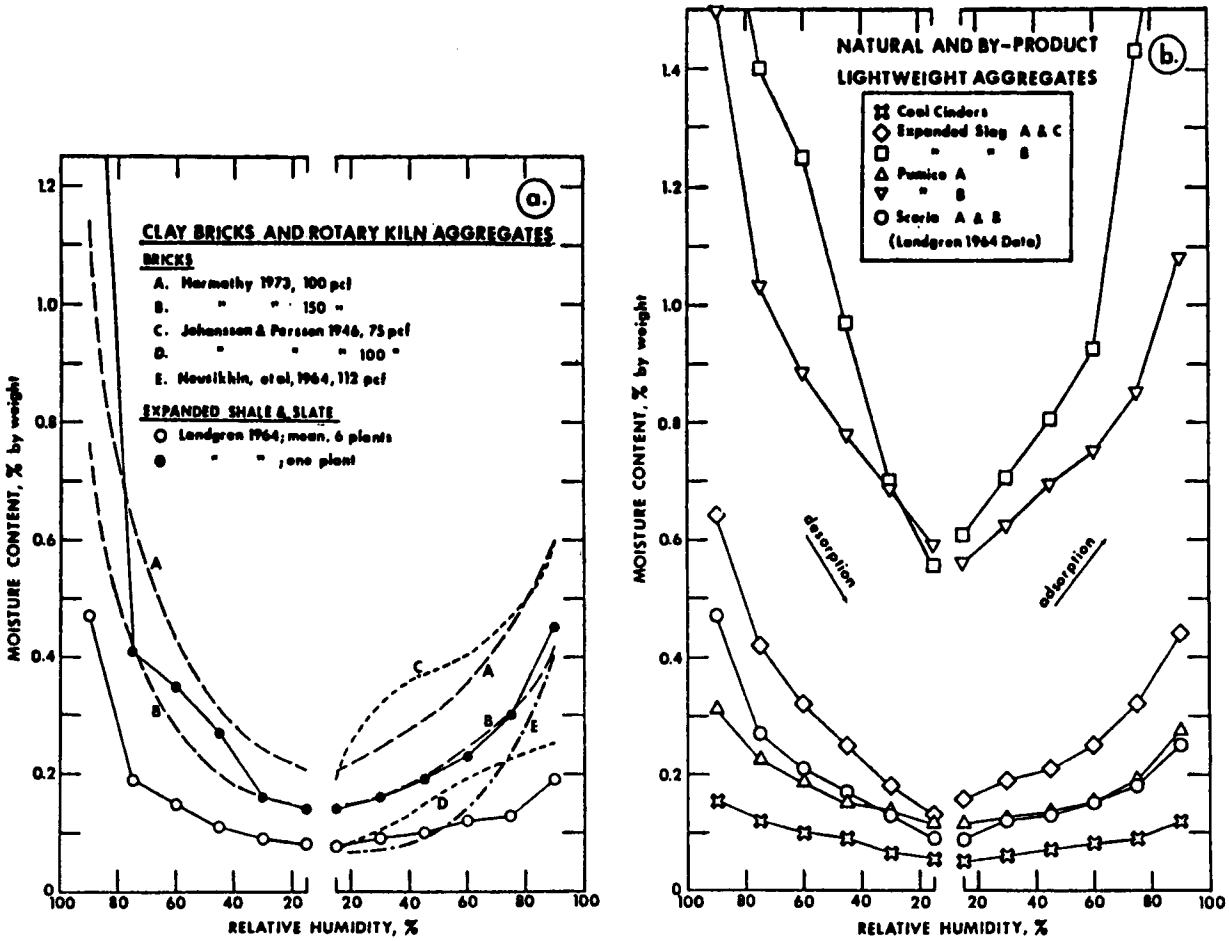

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Fig. 3.20

SORBED MOISTURE CONTENTS FOR LIGHT WEIGHT CONCRETES

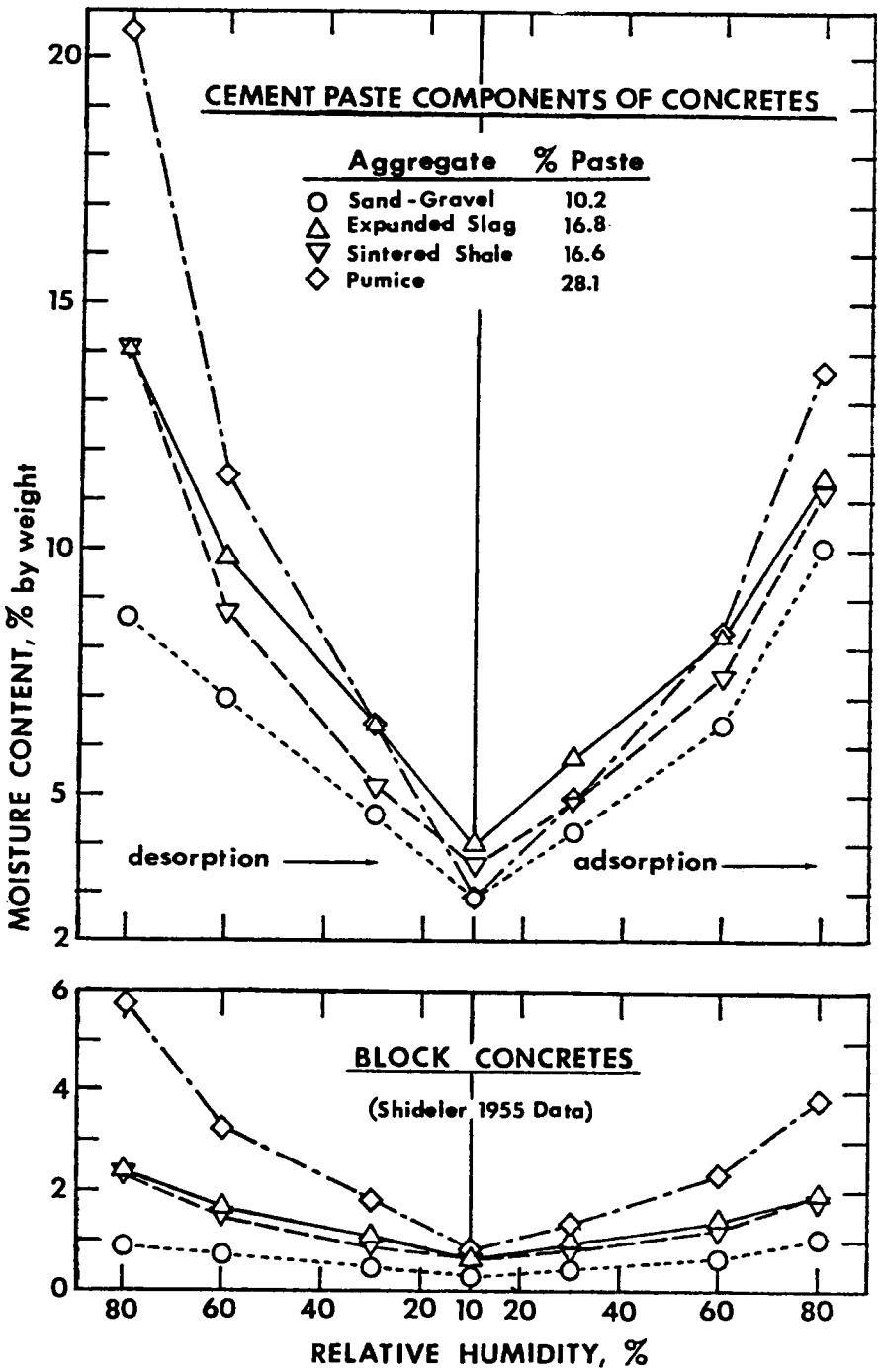

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FIG. 3.21

CALCULATION OF U-VALUE FOR A 8 X 8 X 16 IN. CONCRETE STRETCHER BLOCK

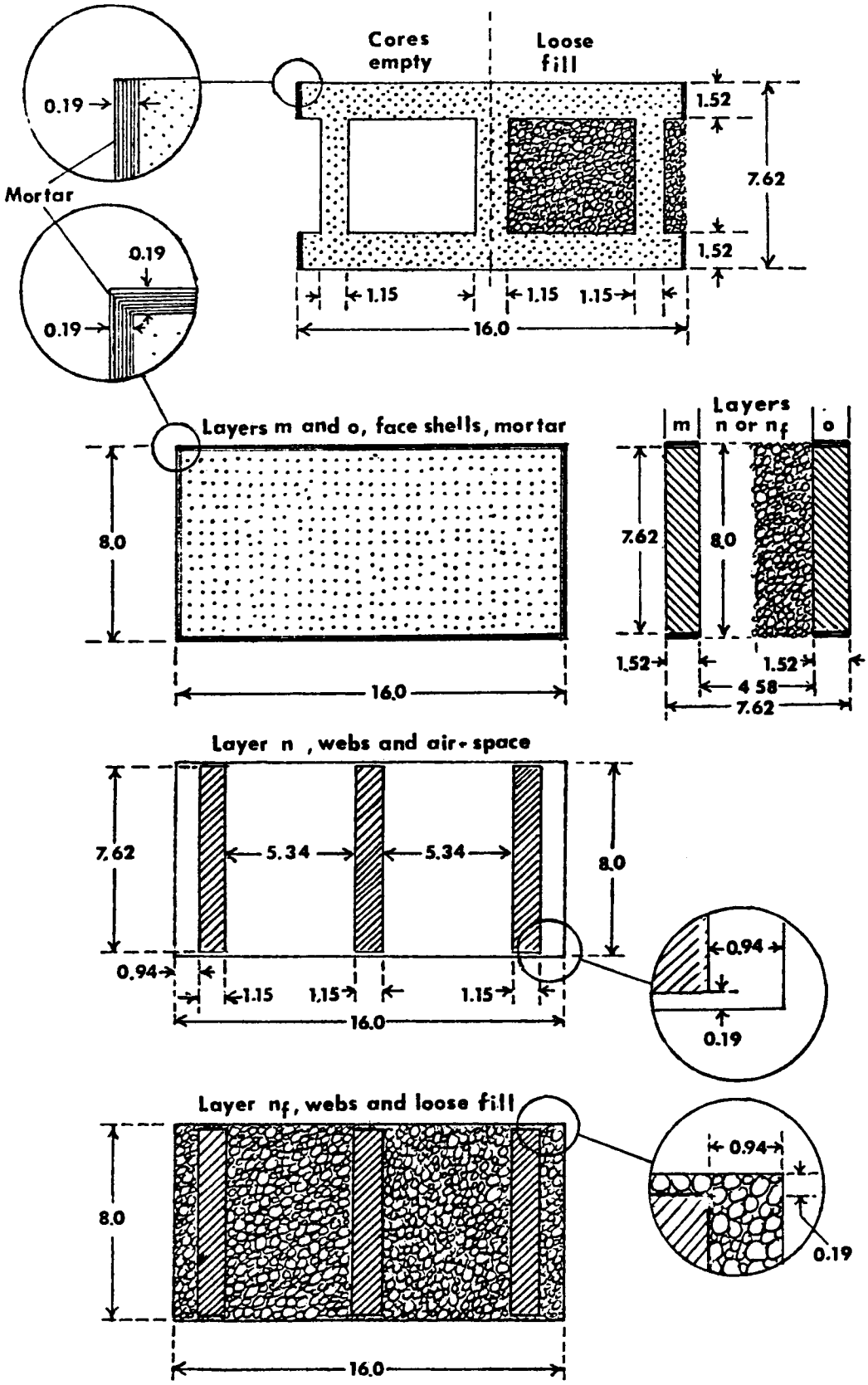

TABLE 3.1 THERMAL CONDUCTIVITY OF OVEN-DRY NORMAL WEIGHT CONCRETES AND MORTARS CALCULATED BY CUBIC MODEL EQUATION FROM THERMAL CONDUCTIVITIES AND FRACTIONAL VOLUMES OF CEMENT PASTE AND AGGREGATE.

Thermal Conductivity		Density of Paste	Thermal Conductivity (λ_c), Btu/h ft^2 (F/in.), and Oven-Dry Density (pcf) of Concretes having Aggregate Fractional Volumes (v_a) of:															
Paste	Aggreg.		0.75		0.70		0.65		0.60		0.55		0.50		0.45		0.40	
p	a	pcf	pcf	λ_c	pcf	λ_c	pcf	λ_c	pcf	λ_c	pcf	λ_c	pcf	λ_c	pcf	λ_c	pcf	λ_c
1.0	10	36	133	5.0	126	4.5	120	4.1	113	3.7	107	3.4	100	3.1	94	2.8	87	2.6
	15			6.1		5.4		4.8		4.3		3.9		3.5		3.2		2.9
	20			6.9		6.0		5.2		4.7		4.2		3.7		3.4		3.0
	30			7.8		6.7		5.8		5.1		4.5		4.0		3.6		3.3
	40			8.4		7.1		6.2		5.4		4.7		4.2		3.8		3.4
	50			8.8		7.4		6.4		5.6		4.9		4.3		3.9		3.4
1.5	10	54	137	6.0	132	5.5	126	5.0	121	4.6	115	4.3	110	3.9	104	3.7	98	3.4
	15			7.5		6.1		6.8		5.5		5.0		4.6		4.2		3.9
	20			8.7		7.7		6.9		6.2		5.6		5.1		4.6		4.2
	30			10.3		8.9		7.9		7.0		6.2		5.6		5.1		4.6
	40			11.3		9.7		8.5		7.5		6.6		5.9		5.3		4.8
	50			12.1		10.3		8.9		7.8		6.9		6.2		5.5		5.0
2.0	10	69	141	6.6	136	6.1	131	5.7	127	5.3	122	5.0	117	4.6	112	4.3	107	4.0
	15			8.5		7.8		7.1		6.5		6.0		5.5		5.1		4.7
	20			10.0		9.0		8.1		7.4		6.7		6.1		5.6		5.1
	30			12.2		10.8		9.6		8.6		7.7		7.0		6.3		5.7
	40			13.7		11.9		10.5		9.3		8.3		7.5		6.7		6.1
	50			14.8		12.8		11.2		9.8		8.8		7.8		7.0		6.3
2.5	10	82	144	7.1	140	6.6	136	6.2	132	5.9	128	5.5	124	5.2	119	4.9	115	4.6
	15			9.3		8.8		7.9		7.3		6.8		6.3		5.8		5.4
	20			11.1		10.1		9.2		8.4		7.7		7.1		6.5		6.0
	30			13.8		12.3		11.0		9.9		9.0		8.2		7.4		6.8
	40			15.7		13.8		12.2		10.9		9.8		8.9		8.0		7.3
	50			17.1		14.9		13.1		11.6		10.4		9.3		8.4		7.6
3.0	10	94	147	7.5	144	7.1	140	6.7	137	6.3	133	5.7	130	5.7	126	5.4	122	5.1
	15			9.9		9.2		8.6		8.0		7.4		6.9		6.5		6.1
	20			11.9		10.9		10.0		9.3		8.5		7.9		7.3		6.8
	30			15.1		13.5		12.2		11.1		10.1		9.2		8.4		7.7
	40			17.4		15.4		13.7		12.4		11.2		10.1		9.2		8.4
	50			19.2		16.8		14.9		13.3		11.9		10.7		9.7		8.8
3.5	10	104	150	7.8	147	7.4	144	7.1	141	6.7	138	6.4	135	6.1	131	5.8	128	5.6
	15			10.4		9.7		9.1		8.6		8.0		7.5		7.1		6.6
	20			12.6		11.7		10.8		10.0		9.3		8.6		8.0		7.4
	30			16.1		14.6		13.3		12.1		11.1		10.2		9.3		8.6
	40			18.8		16.8		15.1		13.6		12.4		11.2		10.3		9.4
	50			20.9		18.5		16.5		14.8		13.3		12.0		10.9		9.9

Notes: Density assumed for aggregates is 165 pcf (2650 kg/m^3); for aggregates of other densities concrete density values given above will be in error.
Multiply pcf density values by 16 to convert to kg/m^3.
Multiply λ_a, λ_c, and λ_p values given above by 0.1442 to convert to W/m K.
Mortar v_a values are less than 0.60; concrete v_a values are greater than 0.60.

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TABLE 3.2 THERMAL CONDUCTIVITY OF OVEN-DRY LIGHT WEIGHT CONCRETE, MORTAR, AND BRICKS OBTAINED FROM DENSITY/THERMAL CONDUCTIVITY LINEAR EQUATIONS

Thermal Conductivity, Btu/h-ft^2-(F/in.), at Oven-Dry Density in pcf*

Material or Type of Aggregate in Concrete	15	20	25	30	40	50	60	70	80	90	100	110	120	130	140	150
1985 ASHRAE Ch. 23	-	0.7	-	0.9	1.15	-	1.7	-	2.5	-	3.6	-	(5.2)	-	(9.0)	-
Neat Cement Paste & Foam Concrete	0.54	0.64	0.75	0.87	1.11	1.39	1.69	2.03	2.41	2.82	3.29	3.80	4.36	-	-	-
Autoclaved Aerated (cellular) Concrete	0.47	0.57	0.67	0.79	1.05	1.34	1.68	2.06	-	-	-	-	-	-	-	-
Autoclaved Micro-porous Silicate	0.41	0.51	0.61	0.72	0.96	1.25	1.58	1.95	2.38	-	-	-	-	-	-	-
Expanded Poly-styrene Beads	0.50	0.62	0.74	0.88	1.18	1.53	1.94	-	-	-	-	-	-	-	-	-
Expanded Perlite	0.46	0.57	0.69	0.83	1.13	1.48	1.90	-	-	-	-	-	-	-	-	-
Exfoliated Vermic-ulite	0.53	0.63	0.74	0.86	1.10	1.38	1.69	-	-	-	-	-	-	-	-	-
Natural Pumice	-	-	-	0.74	1.02	1.35	1.73	2.19	2.71	3.32	4.03	-	-	-	-	-
Sintered Fly Ash & Coal Cinders	-	-	-	-	-	-	1.71	2.11	2.56	3.06	3.64	4.28	-	-	-	-
Volcanic Slag & Scoria	-	-	-	-	-	-	1.67	2.06	2.50	2.99	3.56	-	-	-	-	-
Expanded Slag	-	-	-	-	-	-	1.51	1.84	2.21	2.63	3.10	3.62	4.19	-	-	-
Expanded & Sintered Clay, Shale, Slate	-	-	-	0.87	1.16	1.49	1.88	2.32	2.83	3.40	4.05	4.78	-	-	-	-
Sanded Expanded Clay, Shale, Slate	-	-	-	-	-	1.70	2.21	2.81	3.51	4.32	5.26	6.35	7.60	-	-	-
No-Fines Pumice & Expanded & Sintered Clay, Shale, Slate	-	-	-	0.97	1.27	1.60	1.98	2.40	2.88	3.41	-	-	-	-	-	-
Limestone	-	-	-	-	-	-	-	2.57	3.20	3.94	4.79	5.76	6.88	8.16	9.62	11.27
Cement-Sand Mortar & Foam Concrete	-	-	-	-	-	-	2.35	2.98	3.72	4.58	5.58	6.73	8.05	-	-	-
Fired Clay Bricks	-	-	-	-	-	-	-	2.19	2.62	3.09	3.63	4.22	4.87	5.58	6.39	7.26

*Multiply Btu/h-ft^2-(F/in.) values by 0.1442 to convert to W/m-K; multiply pcf values by 16 to convert to kg/m^3.

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TABLE 3.3 LINEAR REGRESSION CONSTANTS FOR THERMAL CONDUCTIVITY VERSUS DENSITY OF OVEN-DRY CONCRETE, MORTAR, AND CLAY BRICK

Material or Type of Aggregate in Concrete	Number of Data Points n	Regression Equation* Constants a	b	Coefficient of Determination r^2	Mean Deviation, $\lambda'-\lambda$, MD %	Standard Error of λ'/λ, S_y %	MD/S_y
1985 ASHRAE Ch. 23	(6)	0.180	0.295	0.998	-	-	-
Neat Cement Paste & Foam Concrete	31	0.166	0.300	0.98	5.47	7.54	0.73
Autoclaved Aerated (Cellular) Concrete	114	0.132	0.330	0.93	6.25	7.49	0.83
Autoclaved Micro-porous Silicate	31	0.108	0.346	0.94	11.6	15.30	0.76
Expanded Polystyrene Beads	21	0.129	0.350	0.98	4.5	5.53	0.81
Expanded Perlite	54	0.110	0.368	0.93	8.1	9.80	0.83
Exfoliated Vermiculite	35	0.165	0.301	0.92	7.4	9.17	0.81
Natural Pumice	33	0.096	0.374	0.94	6.3	7.80	0.81
Sintered Fly Ash & Coal Cinders	48	0.129	0.332	0.80	8.0	9.4	0.85
Volcanic Slag & Scoria	(5)**	0.125	0.335	—	-	-	-
Expanded Slag	100	0.130	0.317	0.87	7.0	8.87	0.79
Expanded & Sintered Clay, Shale, Slate	129	0.135	0.34	0.98	5.8	7.49	0.77
Sanded Expanded Clay, Shale, Slate	43	0.118	0.381	0.88	6.15	7.73	0.80
No-Fines Pumice & Expanded & Sintered Clay, Shale, Slate	39	0.175	0.313	0.98	4.2	5.13	0.82
Limestone	30	0.106	0.381	0.92	8.0	9.89	0.81
Cement-Sand Mortar & Foam Concrete	18	0.120	0.384	0.91	9.6	13.1	0.73
Sand & Gravel	40	0.29	0.29	0.17	15.9	-	-
Fired Clay Bricks	35	0.165	0.309	0.74	11.0	13.1	0.84

* Equation in the form: $\lambda' = ae^{bp^{0.5}}$ in which λ' is calculated by the equation in Btu/h-ft^2-(F/in.) and p is the dry density in pcf; to obtain values in W/m-K for p in kg/m^3, multiply a values by 0.1442 and b values by 0.25; e = 2.72.

** USSR SNiP II-3-79 (1979) values;

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TABLE 3.4 THERMAL CONDUCTIVITY MOISTURE FACTORS FOR CONVERTING THERMAL CONDUCTIVITY OF OVEN-DRY CONCRETES AND CLAY BRICKS TO PRACTICAL DESIGN VALUES

Material, or Type of Aggregate in Concrete	Type of Exposure	Relative Humidity Mean, %	Moisture Content % by Weight	Thermal Conductivity Moisture Factor, % Increase in Thermal Conductivity per 1% Moisture Content	Practical Thermal Conductivity Multiplier
Neat Cement Paste & Foam Concrete; Expanded Polystyrene Bead Concrete	Pr	60	8.0	3.0	1.25
Autoclaved Aerated (Cellular) Concrete	Pr	60	4.5	4.5	1.20
Expanded Perlite & Exfoliated Vermiculite	Pr	60	6.5	4.5	1.30
Natural Pumice	Pr	60	5.5	4.25	1.22
	Un	80	7.0	4.25	1.30
Sintered Fly Ash, Scoria & Coal Cinders	Pr	60	3.75	6.0	1.22
	Un	80	5.0	6.0	1.30
Expanded Slag	Pr	60	3.5	5.5	1.20
	Un	80	5.5	5.5	1.30
Expanded & Sintered Clay, Shale, Slate (no natural sand); Sanded Expanded Slag	Pr	60	3.5	4.0	1.14
	Un	80	5.5	4.0	1.22
Sanded Expanded & Sintered Clay, Shale & Slate	Pr	60	3.0	5.0	1.15
	Un	80	5.0	5.0	1.25
Limestone	Pr	60	2.0	7.0	1.15
	Un	80	3.0	7.0	1.22
Sand-Gravel, <50% Quartz or Quartzite	Pr	60	2.0	7.0	1.15
	Un	80	3.0	7.0	1.22
Sand-Gravel, >50% Quartz or Quartzite	Pr	60	2.0	9.0	1.18
	Un	80	3.0	9.0	1.27
Cement Mortar, Sanded	Pr	60	2.0	9.0	1.20
Foam Concrete	Un	80	3.0	9.0	1.30
Clay Bricks	Pr	60	0.5	30.0	1.15
	Un	80	2.0	20.0	1.40

Pr = Protected exposure: Exterior wall stuccoed or coated with cement base, "texture" or latex paint; interior wythe of cavity wall or of composite wall with full collar joint.

Un = Unprotected: Exterior wall surface uncoated, or treated with water repellent or thin clear polymeric "sealer" only.

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TABLE 3.5 SUGGESTED "PRACTICAL" THERMAL CONDUCTIVITY DESIGN VALUES FOR NORMAL WEIGHT AND LIGHT WEIGHT CONCRETES, SOLID CLAY BRICKS AND CEMENT MORTARS

			Practical Thermal Conductivity in Btu/h-ft^2-(F/in.) at Oven-Dry Density in pcf[a]															
Group	Material or Type of Aggregate in Concrete	Exposure Type[b]	15	20	25	30	40	50	60	70	80	90	100	110	120	130	140	150
Matrix - Insul.	Neat Cement Paste & Foam Concrete	Pr	0.7	0.8	0.9	1.1	1.4	1.7	2.1	2.5	3.0	3.5	4.1	4.7	5.4	-	-	-
Insul., Struct.	Autoclaved Aerated (Cellular)	Pr	0.6	0.7	0.8	1.0	1.3	1.6	2.0	2.5	-	-	-	-	-	-	-	-
Insul.	Expanded Polystyrene Beads, Perlite, Vermiculite, Expand, Glass	Pr	0.65	0.8	0.95	1.1	1.5	1.9	2.4	-	-	-	-	-	-	-	-	
Blocks, Struct.	Unsanded Expand. & Sint. Clay, Shale, Slate, Fly Ash; Cinders, Scoria, Pumice; Sand-Exp. Slag	[c]																
		Pr	-	-	-	-	1.3	1.7	2.1	2.6	3.25	4.0	4.65	5.5	6.4	-	-	-
		Un	-	-	-	-	1.4	1.8	2.3	2.8	3.5	4.25	5.0	5.9	6.8	-	-	-
Blocks, Struct.	Unsanded Expanded Slag	Pr	-	-	-	-	-	-	1.8	2.2	2.7	3.2	3.7	4.3	-	-	-	-
		Un	-	-	-	-	-	-	2.0	2.4	2.9	3.4	4.0	4.7	-	-	-	-
Blocks, Struct.	Sanded Expanded & Sint. Clay, Shale, Slate, Fly Ash; Sanded Pumice, Scoria, Cinders	Pr	-	-	-	-	-	1.9	2.5	3.2	4.1	5.1	6.2	7.6	9.1	-	-	-
		Un	-	-	-	-	-	2.1	2.7	3.5	4.4	5.5	6.8	8.2	9.9	-	-	-
Blocks, Struct.	Limestone	Pr	-	-	-	-	-	-	-	-	-	-	5.5	6.6	7.9	9.4	11.1	13.8
		Un	-	-	-	-	-	-	-	-	-	-	5.85	7.0	8.3	10.0	11.7	13.75
Blocks, Struct.	Sand-Gravel, <50% Quartz or Quartzite	Pr	-	-	-	-	-	-	-	-	-	-	-	-	-	10.0	13.8	18.5
		Un	-	-	-	-	-	-	-	-	-	-	-	-	-	10.7	14.6	19.6
Blocks, Struct.	Sand-Gravel, >50% Quartz or Quartzite	Pr	-	-	-	-	-	-	-	-	-	-	-	-	-	11.0	15.3	20.5
		Un	-	-	-	-	-	-	-	-	-	-	-	-	-	11.8	16.5	22.0
Insul., Struct.	Cement-Sand Mortar; Sanded Foam Concrete	Pr	-	-	-	-	-	-	2.8	3.6	4.5	5.5	6.7	8.1	9.7	11.5	13.5	-
		Un	-	-	-	-	-	-	3.1	3.9	4.8	6.0	7.3	8.7	10.5	12.4	14.7	-
Masonry	Solid Clay Bricks	Pr	-	-	-	-	-	-	-	2.5	3.0	3.6	4.2	4.9	5.6	6.4	7.4	8.4
		Un	-	-	-	-	-	-	-	3.1	3.7	4.3	5.1	5.9	6.8	7.8	9.0	10.2

[a] Multiply Btu/h-ft^2-(F/in.) values by 0.1442 to convert to W/m K; multiply pcf values by 16.03 to convert to kg/m^3.

[b] Pr = Protected exposure; mean relative humidity in wall up to 60 percent. Exterior wall surface coated with stucco, cement-base paint or continuous coating of latex paint; or inner wythe of composite wall with a full collar joint, or inner wythe of cavity wall. Un = "unprotected" exposure; mean relative humidity in wall up to 80 percent. Exterior wall surface uncoated or treated with a water repellent or clear sealer only.

[c] Densities above 100 pcf do not apply to pumice or expanded clay or shale concretes.

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TABLE 3.6 EQUILIBRIUM MOISTURE CONTENT OF AUTOCLAVED AERATED (CELLULAR) CONCRETES VERSUS RELATIVE HUMIDITY FROM WATER VAPOR ABSORPTION ISOTHERMS.

Source	Components # Binder	Siliceous	Density kg/m^3*	Moisture Content, % by Weight, at Relative Humidity of: 40%	60%	80%
Houst, et al (1983)	Lime, PC	Quartz	307	2.2	2.5	3.0
" " "	"	"	386	2.25	2.65	3.25
" " "	"	"	501	2.2	2.6	3.05
Prim & Wittmann (1983)	Lime, PC	Quartz	508	0.9	1.3	1.8
" " "	"	"	579	0.9	1.3	1.9
" " "	"	"	597	0.95	1.4	2.15
" " "	"	"	720	1.05	1.7	2.8
Plonski (Lewicki, 1967)	Lime, PC	Quartz	700	1.6	2.2	3.6
" " "	"	"	500	1.95	2.5	4.2
" " "	"	"	300	2.35	3.25	5.3
Johansson & Persson (1946)	PC	Quartz	400	2.7	3.0	3.4
" " "	Lime	Shale Ash	-	2.75	3.5	6.0
Schaffler (Granholm 1960)	-	Fly Ash	500-600	4.0	8.2	-
" " "	-	-	" "	3.5	6.0	-
" " "	-	Quartz	500-600	2.8	4.2	-
" " "	-	"	" "	2.3	3.3	-
Neusikhin, et al (1964)	Lime	Quartz	950	2.4	3.1	4.3
" " "	"	"	900	1.3	1.9	2.6
Garnashevich & Galuzo (1979)	Lime	Shale Ash	700	1.0	1.4	2.3
" " "	"	"	740	1.4	2.25	3.8
" " "	"	"	720	1.6	2.65	3.7
Dimitriu-Vilcea (1965)	-	Quartz	400	2.5	3.25	5.0
" " "	-	-	500	2.4	3.0	4.6
" " "	-	-	600	2.25	2.85	4.5
" " "	-	-	700	2.15	2.8	4.15
USSR SNIP II-3-79 (1979)	Lime, PC	Quartz	1000	-	10[a]	15[b]
" " " "	" "	"	800	-	"	"
" " " "	" "	"	600	-	8[a]	12[b]
" " " "	" "	"	400	-	"	"
" " " "	" "	"	300	-	"	"
" " " "	PC	Fly Ash	1200	-	15[a]	22[b]
" " " "	" "	" "	1000	-	"	"
" " " "	" "	" "	800	-	"	"

#PC = Portland Cement.
* Multiply kg/m^3 values by 0.0624 to convert to pcf.
[a] At 50% to 60% relative humidity
[b] At 60% to 75% relative humidity

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TABLE 3.7 EQUILIBRIUM MOISTURE CONTENT OF INSULATING CONCRETES, MORTARS AND CEMENT PASTES VERSUS RELATIVE HUMIDITY

Source	Proportions* or Additions	Moist Cure Days	Density* pcf	Moisture Content, % by Weight, at Relative Humidity, of: 40%	50%	60%	80%	Comments
Expanded Perlite Concretes and Mortars								
Gustaferro, et al (1971)	-	5	29	6.5	-	9.9	14.5	Desorption
" " "	plus sand	5	58	3.5	-	5.1	6.5	"
" " "	plus sand	5	74	0.8	-	1.5	3.2	"
Valore (1955)	-	2	32	-	9.8	-	-	100 Days 50% R.H.
FIP (1977)	-	-	25-62	-	-	8.0[d]	10.0[e]	Various codes
USSR SNIP II-3-79 (1979)	-	-	37-75	-	-	10.0[d]	15.0[e]	Standard values
" " " "	-	-	50-62	-	-	7.0[d]	12.0[e]	" "
Exfoliated Vermiculite Concretes								
Gustaferro, et al (1971)	-	5	28	7.2	-	10.0	14.1	Desorption
" " "	plus sand	5	54	5.6	-	7.8	12.9	"
" " "	plus sand	5	70	3.9	-	5.0	6.5	"
Valore (1955)	-	2	32	-	7.3	-	-	100 Days 50% R.H.
Popov (1964)	-	-	24	2.8	-	4.0	7.1	Adsorption
FIP (1977)	-	-	19-44	-	-	8.0[d]	13.0[e]	Various codes
USSR SNIP II-3-79 (1979)	-	-	19-50	-	-	8.0[d]	13.0[e]	Standard values
Mortars								
Johansson & Persson (1946)	1:3[a]	-	-	1.0	-	1.4	1.85	Adsorption
" " "	1:3[b]	-	-	0.4	-	0.6	1.0	"
" " "	1:1:6[c]	-	-	0.7	-	1.0	1.6	"
Powers & Brownyard (1946)	1:1.6[a]	7	-	2.4	-	3.1	4.0	Adsorption
" " "	1:2.6[a]	7	-	1.8	-	2.5	3.4	"
" " "	1:3.6[a]	7	-	1.35	-	1.8	2.75	"
USSR SNIP II-3-79 (1979)	a	-	112	-	-	2.0[d]	4.0[e]	Standard values
" " " "	b	-	100	-	-	2.0[d]	4.0[e]	" "
" " " "	c	-	106	-	-	2.0[d]	4.0[e]	" "
Foam Concretes								
Gustaferro, et al (1971)	neat	5	30	9.5	-	13.3	18.0	Desorption
" " "	1:1[a]	5	58	3.9	-	5.8	8.4	"
" " "	1:2.1[a]	5	78	3.2	-	4.1	5.8	"
" " "	1:3.2[a]	5	100	1.6	-	2.3	3.9	"
Valore (1955)	neat	2	34	-	11.5	-	-	100 Days 50% R.H.
Neat Portland Cement Pastes								
Johansson & Persson (1946)	w/c 0.4	-	-	5.5	-	7.4	10.1	Adsorption
Powers & Brownyard (1946)	w/c 0.3-0.6	7	-	6.1	-	8.0	11.0	Adsorption
" " "	" "	180	-	7.8-9.4	-	9.6-12.2	12.0-16.0	"
Sereda, et al (1966)	w/c 0.5-0.7	130	-	8.0	-	10.5	14.0	"
" " "	w/c 0.4	"	-	8.0	-	10.0	13.0	"
Spooner (1977)	w/c 0.35-0.71	-	-	-	-	9.2-10.4[f]	-	Desorption
" "	w/c 0.83-0.95	-	-	-	-	6.4-6.9[f]	-	"
Shielder (1955)	-		-	5.0-6.5	-	6.4-8.3	10.0-13.6	2-year desorption-adsorption cycle.[h]

*Multiply pcf values by 16.03 to convert to kg/m³

*Proportions are by volume

[a] Portland cement: sand

[b] lime: sand

[c] cement: lime: sand

[d] 50 to 60% or less than 60% relative humidity.

[e] over 60% or 60 to 76% relative humidity

[f] 65% relative humidity

[g] Steam cure

[h] Calculated on cement paste fraction of concrete blocks

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TABLE 3.8 EQUILIBRIUM MOISTURE CONTENT OF CONCRETE VERSUS RELATIVE HUMIDITY FOR VARIOUS LIGHTWEIGHT AGGREGATE CONCRETES

Source	Concrete Type	Cure	Density pcf	Moisture Content, % by Weight at Relative Humidity, 40%	50%	60%	70%	80%	Comments
Expanded Slag Aggregate									
Kalousek & Selden (1953)	B1	M	103	3.0[a]	-	4.1[a]	4.3	4.7[b]	30-35 day desorption
" " "	"	St	"	2.6[a]	-	3.4[a]	3.8	4.3[b]	" " "
" " "	"	H	"	1.2[a]	-	2.0[a]	2.5	3.0[b]	" " "
Kuenning & Carlson (1956)	"	St	97	-	3.1	-	-	-	90 days at 50% R.H.
Valore & Kuenning (1962)	"	St	104	-	3.9	-	-	-	57 days at 50% R.H.
" " "	"	H	105	-	2.4	-	-	-	24 " " "
Toennies (1961)	B1**	St	91	2.2	-	4.2	-	6.8	Ultrarapid (1 hour)
" "	B1	St	104-122	1.8	-	2.9	-	4.5	" "
" "	"	H	94-98	1.0	-	1.6	-	3.9	" "
" "	B1*	St	97	2.3	-	3.6	-	5.9	" "
" "	"	H	122	0.5	-	0.9	-	1.8	" "
Shideler (1955)	B1	St	100	1.1	-	1.4	-	2.0	2 year desorption-adsorption cycle
Johansson & Persson (1946)	Str	-	-	1.8	-	2.4	-	3.0	adsorption
Spivak (1979)	Str	-	-	0.4	-	0.9	-	1.8	adsorption
" "	"	-	-	1.0	-	1.2	-	2.1	"
Rudnai (1963)	"	-	72-94	1.5	-	2.0	-	2.3	adsorption
FIP (1977)	"	-	50-100	-	-	6.0[c]	-	8.8[d]	mean, various codes
USSR SNIP II-3-79 (1979)	Str	-	62-112	-	-	5.0[c]	-	8.0[d]	standard values
Cinder, Coal Slag and Sintered Fly Ash Aggregates									
Kalousek & Selden (1953)	B1	M	96	2.2[a]	-	3.3[a]	3.8	4.3[b]	30-35 day desorption
" " "	"	St	"	2.3[a]	-	2.9[a]	3.25	3.7[b]	" " "
" " "	"	H	"	1.2[a]	-	1.9[a]	2.3	2.8[b]	" " "
Kuenning & Carlson (1956)	B1	St	100	-	2.25	-	-	-	90 days at 50% R.H.
Valore & Kuenning (1962)	B1	H	88	-	3.8	-	-	-	52 days at 50% R.H.
" " "	"	H	92	-	2.1	-	-	-	28 days at 50% R.H.
Toennies (1961)	B1	St	90	2.5	-	4.0	-	5.8	Ultrarapid (1 hour)
" "	B1**	H	91-97	1.9	-	3.0	-	4.3	" "
Rudnai (1963)	Str''	-	70-93	2.0	-	2.65	-	3.1	Adsorption
Arejewicz & Tolstych (Pionski, 1973)	Str	-	-	2.4	-	3.7	-	6.0	Adsorption
USSR SNIP II-3-79 (1979)	"	-	62-87	-	-	5.0[c]	-	8.0[d]	Standard Values
Rudnai (1963)	Str	-	70-93	2.3	-	3.0	-	3.7	Adsorption
USSR SNIP II-3-79 (1979)	Str'	-	62-100	-	-	5.0[c]	-	8.0[d]	Standard Values
Natural Pumice Aggregate									
Kalousek & Seldon (1953)	B1	M	65	4.7[a]	-	6.4[a]	7.2	8.0[b]	30-35 day desorption
" " "	"	St	65	3.7[a]	-	5.5[a]	5.9	7.0[b]	" " "
" " "	"	H	65	2.7[a]	-	4.3[a]	5.1	6.0[b]	" " "
Kuenning & Carlson (1956)	B1	St	70	-	3.9	-	-	-	90 days at 50% R.H.
Valore & Kuenning (1962)	"	St	64	-	5.8	-	-	-	62 days at 50% R.H.
" " "	"	H	64	-	6.3	-	-	-	38 " " "
Toennies (1961)	B1	St	65-75	6.7	-	9.3	-	14.2	Ultrarapid (1 hour)
" "	"	H	63	6.4	-	10.3	-	15.4	" "
Shideler (1955)	B1	St	72	1.7	-	2.35	-	3.8	2-year desorption-adsorption cycle
USSR SNIP II-3-79 (1979)	Str	-	50-100	-	-	4.0[c]	-	6.0[d]	Standard values
Scoria and Volcanic Slag Aggregates									
Toennies (1961)	B1	St	97	2.1	-	3.3	-	4.0	Ultrarapid (1 hour)
" "	"	H	97	1.1	-	2.4	-	5.8	" "
Rudnai (1963)	Str	-	72-94	3.1	-	4.0	-	4.9	Adsorption
USSR SNIP II-3-79 (1979)	Str	-	50-100	-	-	7.0[c]	-	10.0[d]	Standard values

Concrete Type: B1 = bloc; Str = structural. Cure: M = moist; St = steam; H = autoclave.

[a] Interpolated;
[b] Extrapolated;
[c] 50 to 60% or less than 60% relative humidity
[d] over 60% or 60 to 75% RH

**Sand added *Limestone added
'Coal slag
''Sintered fly ash

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TABLE 3.9 EQUILIBRIUM MOISTURE CONTENT OF CONCRETE VERSUS RELATIVE HUMIDITY FOR ROTARY KILN EXPANDED OR SINTERED CLAY OR SHALE AGGREGATE AND FOR NORMAL WEIGHT AGGREGATE CONCRETES

Source	Concrete Type	Cure	Density pcf	Moisture Content, % by Weight at Relative Humidity, of: 40%	50%	60%	70%	80%	Comments
Rotary Kiln Clay and Shale Aggregates									
Brewer (1969)	B1	St	85	1.75	-	2.15	-	2.85	ASTM C236 Hot-Box Test
Kalousek & Selden (1953)	B1	M	80	2.2[a]	-	3.1[a]	3.6	4.2[b]	30-35 day desorption
" " "	"	St	80	1.8[a]	-	2.6[a]	2.9	3.5[b]	" " "
" " "	"	H	80	1.0[a]	-	1.5[a]	1.7	2.0[b]	" " "
Kuenning & Carlson (1956)	"	St	84	-	2.5	-	-	-	90 days at 50% R.H.
Toennies (1961)	"	St	79-101	2.2	-	3.3	-	4.3	1 hour ultrarapid
" "	"	H	91-101	1.0	-	1.7	-	2.9	" "
Valore & Kuenning (1962)	"	St	80	-	3.9	-	-	-	40 days at 50% R.H.
" " "	"	H	81	-	2.4	-	-	-	34 " " " "
FIP (1977)	"	-	41	-	-	4.0[c]	-	7.0[d]	Mean, European Codes
" "	"	-	41	-	-	-	-	2.0[d]	Ventilated
Brewer (169)	Str	-	86	1.7	-	2.1	-	2.7	ASTM C236 Hot-Box Test
Strogonov (Ushkov et al, 1978)	Str-Ins	-	60-73	-	-	2.0		2.9	Adsorption
Reichard (1970)	Str	St	79-100	-	1.0-2.8	-	-	-	18 aggregates, 5-year desorption, 50% R.H.
FIP (1977)	Ins	-	25-37	-	-	2.0[c]	-	6.0[d]	Mean, various
" "	"	-	50	-	-	4.0[c]	-	10.0[d]	European codes
" "	Str	-	62-100	-	-	3.0[c]	-	10.0[d]	
USSR SNIP II-3-79 (1979)	Str-Ins	-	25-112			4.0[c] 5.0[c]	-	7.0-10.0[d]	Standard values
Sintered Clay and Shale Aggregates									
Shideler (1955)	B1	St	89	1.0	-	1.3	-	1.8	2-year desorption-adsorption cycle.
Kalousek & Selden (1935)	"	M	89	2.8[a]	-	3.6[a]	4.0	4.4[b]	30-35 day desorption
" " "	"	St	89	2.2[a]	-	3.2[a]	3.5	4.0[b]	" " "
" " "	"	H	89	1.2[a]	-	2.2[a]	2.6	3.1[b]	" " "
Neusikhin, et al (1964)	Str	-	76	0.8	-	1.15	-	2.8	Adsorption
Sand-Gravel and Limestone Aggregates									
Kuenning & Carlson (1956)	B1	St	139	-	1.4	-	-	-	90 days at 50% R.H.
Toennies (1961)	"	St	136	0.8	-	1.2	-	1.9	Ultrarapid (1 hour)
" "	"	H	135	0.5	-	1.0	-	1.5	" "
Valore & Kuenning (1962)	"	St	136	-	1.5	-	-	-	34 days at 50% R.H.
" " "	"	H	133	-	0.8	-	-	-	21 " " "
Shideler (1955)	"	St	138	0.5	-	0.75	-	1.0	2-year desorption-adsorption cycle
Kalousek & Selden (1935)	"	M	135	1.1[a]	-	1.5[a]	1.7	2.0[b]	30-35 day desorption
" "	"	St	"	0.9[a]	-	1.2[a]	1.3	1.5[b]	" " "
" "	"	H	"	0.6[a]	-	1.0[a]	1.2	1.4[b]	" " "
Johansson & Persson (1946)	"	-	-	0.5	-	0.7	-	0.9	Adsorption
Toennies* (1961)	"	St	128	0.9	-	1.3	-	1.5	Ultrarapid (1 hour)
" "	"	H	136	0.5	-	0.9	-	1.6	" "
Brewer (1969)	Str	M	147	1.4	-	1.7	-	2.2	ASTM C236 Hot-Box Test
Reichard (1970)	Str	St	142	-	1.0	-	-	-	5 years at 50% R.H.
Johansson & Persson (1946)	-	-	-	0.9	-	1.3	-	1.85	Adsorption
Lewicki* (1969)	Str	-	69-100	0.55	-	0.7	-	1.0	"
USSR SNIP II-3.-79 (1979)	Str	-	150-156	-	-	2.0[c]	-	3.0[b]	Standard values

Concrete Type: B1 = block; Str = structural; Ins = insulating; Cure: M = moist; St = steam; H = autoclave.

[a] Interpolated
[b] Extrapolated
[c] 50 to 60 % or less than 60% relative humidity
[d] over 60% or 60 to 75% relative humidity
*Multiply pcf values by 16.03 to convert to kg/m^3
*Limestone aggregate.

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TABLES 3.10 THERMAL CONDUCTIVITY MOISTURE FACTORS FOR AUTOCLAVED AERATED (CELLULAR) CONCRETES.

Source	Type*	Density# kg/m³	Moisture Content % by Weight	Thermal Conductivity Moisture Factor, % Increase in Thermal Conductivity per 1% of Moisture	
				Mean	Range
Jespersen (1953)	A	445-650	15-22	4.3	4.2-4.4
" "	D	590-740	13-17	5.35	5.1-5.6
Krischer & Esdorn (1956)	A & D	520-640	3.6-118	4.4	3.6-5.2
Jonell (1960)	A	400-500	-	5.1	5.0-5.4
Saare & Jansson (1960)	A	435-595	13-18	4.1	3.1-5.2
Dimitriu-Vilcea (1965)	-	400-750	6.7-60	5.4	3.8-6.2
Paljak (1967)	A & D	488-502	1.3-18	4.1	3.9-4.4
" (1973)	D	500-516	6.3-15	3.7	3.3-4.0
Loudon (1983)	C	490-876	2.0-17	3.5	3.1-3.8
Sandberg** (1985)	-	300-876	-	4.1	1.7-6.4
" "	-	" "	-	4.0	2.9-5.2
Makarichev & Levin (1961, cited by Lewicki, 1967)	-	300-1200	2.4-10	3.7	2.5-4.4
Stefanski (Plonski, 1973b)	-	700	5.0-20	3.4	3.3-3.5
Dimitrov (1965)	-	450-720	3.0-20	5.6	5.4-5.8
Plonski (1973b)	A	500-700	5.0-25	5.0	3.8-6.1
" "	C	500-700	5.0-25	5.0	3.2-6.0
Kaufman (1955; Lewicki, 1967)	-	700	5.0-20	7.6	7.4-7.9
Garnashevich & Galuzo (1979)	B	715-740	3.0-12	3.5	2.1-3.9
USSR SNIP II-3-79 (1979)	A & B	300-1000	8.0-15	4.9	3.6-7.3
" " " "	C	800-1200	15.0-22	5.6	4.6-6.7

*Type: A = portland cement or lime and cement and ground quartzitic sand.
B = lime and quartzitic sand.
C = portland cement or lime and cement and fly ash
D = lime and shale ash.

#Multiply kg/m³ values by 0.0624 to convert to pcf.

**Sandberg reviewed 15 literature sources including 7 of the first 8 listed above. The second listing for him excludes 3 extreme values in his group of 40 determinations.

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TABLE 3.11 THERMAL CONDUCTIVITY MOISTURE FACTORS FOR VARIOUS LIGHT WEIGHT AGGREGATE CONCRETES AND NEAT PORTLAND CEMENT PASTES.

Source	No. of Data Points	Density* pcf	Moisture Content % by weight	Thermal Conductivity Moisture Factor, % Increase in Thermal Conductivity per 1 % of Moisture: Mean	Range
			Expanded Slag Aggregate		
Plonski (1973a)	3	75-103	-	6.5	5.1-8.2
" "	4	62-84	3.5-7.0	6.3	5.3-7.5
J.S. Cammerer (1939)	6	56-112	1.2-3.3	5.2	3.7-6.7
" "	1	91	0.7-2.1	12.2	-
Grigoriev (1963)	4	62-100	5.0-10	4.7	4.3-5.4
Natslevski (1977)	9	74-111	3.4-8.4	5.5	3.4-7.8
Spooner (1980)	1	87	5.5-18	4.6	linear
USSR SNIP II-3-79 (1979)	5	62-100	5.0,8.0	6.1	4.4,7.5
" " "	5	50-100**	8.0,11	6.3	4.5,9.1
			Coal Cinders Aggregate		
Lewicki (1967)	6	62-91	3.5-10	5.9	4.3-7.6
Arijewicz & Tolstych#	-	94	3.3-20	6.4	5.4-8.0
Franczuk#	-	94	5.0-20	6.4	5.4-8.0
Kaufmann#	-	74-97	4.2-6.7	13.0	10.0-15
Dimitrov (1965)	4	65-80	5.0-35	3.8	3.7-4.1
USSR SNIP II-3-79 (1979)	3	62-87	5.0,8.0	3.9	2.5-5.4
			Natural Pumice Aggregate		
Krischer & Esdorn (1956)	2	49-54	72.0-82##	3.3	3.1.3.5
J.S. Cammerer (1939)'	1	45	3.2	4.6	4.3-4.9
Ryutani (1965)	1	86	2.4-14.5	4.8	linear
USSR SNIP II-3-79 (1979)	5	50-100	7.0,10	3.9	2.5,6.9
			Exfoliated Vermiculite Aggregate		
Popov (1964)	9	18-69	5.0	5.3	2.9-6.7
Morozov (Lewicki, 1967)	7	21-69	5.0	6.0	4.6-6.6
Ball (1968)''	6	25-21	4.8-8.3	(4.3)	(2.4-6.4)
USSR SNIP II-3-79	4	19-50	8.0,13	2.0	1.4,2.9
			Expanded Perlite Aggregate		
Van Geem, et al (1982)	4	46	29-49	4.1	3.5-4.7
Zhukov (1962)	15	34-59	7.0-30	2.5	0.8-4.9
Tye & Spinney (1976)	1	24	27.0-66	2.1	1.4-2.5
USSR SNIP II-3-79 (1979)	4	37-75	10.0,15	5.7	4.7,6.7
			Neat Cement Paste		
Spooner (1977)	6	64-108	6.1-10.4	1.9	1.1-2.4

*Multiply pcf values by 16.03 to convert to kg/m^3.
**Aerated.
' Mean temperatures 0, 10, & 20 C.
#Cited by Lewicki (1967).
##Saturated
''Ball's values in parentheses are "reverse" factors using the equation

$$LAMBDA = 0.165e^{0.301P^{0.5}}$$

USSR SNIP values are standard values based on tests.

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TABLE 3.12 THERMAL CONDUCTIVITY MOISTURE FACTORS FOR ROTARY KILN AND SINTERED CLAY AND SHALE CONCRETES, WITHOUT AND WITH NATURAL SAND.

Source	No. of Data Points	Density* pcf	Moisture Content % by weight	Thermal Conductivity Moisture Factor, % Increase in Thermal Conductivity per 1% of Moisture Mean	Range
		Rotary Kiln Aggregates Without Natural Sand			
Natsievski (1977)	9	57-82	7.6-18.1	3.3	1.3-4.0
Schule, et al (1976)	4	66-85	3.7-4.8	3.1	2.9-3.4
" " "	3	77-81	3.9-4.2	3.3	3.1-3.5
Schule & Kupke (1972)	1	77	2.5-28.1	4.0	3.8-4.2
" " "	3	72-84	4.4-5.7	3.1	2.2-4.2
Lewicki (1967)	-	50-100	-	6.0	5.5-6.5
Lentz & Monfore* (1965)	1	89	7.9-11.2	3.4	3.2-3.6
Petersen (1948)	1	61	1.7-7.3	4.2	-
Tye & Spinney (1976)	1	85	3.5-13.0	4.4	4.1-4.7
Spivak (Pionski, 1973a)	-	various	-	3.4	1.6-5.7
Jespersen (1953)	1	28	5.0-10	4.6	3.8-5.5
Dimitrov (1965)	3	53-71	6.0-25	3.5	3.3-3.8
" "	1	103	4.6-13	4.3	6.1-3.0
USSR SNIP II-3-79 (1979)	11	31-112	5.0,10	4.7	3.2-7.3
		Sintered Aggregates Without Natural Sand			
Natsievski (1977)	6	74-107	4.1-8.4	3.3	3.0-3.6
Lewicki (1967)	1	66	5.0-20	5.1	4.6-5.5
Stein & Tachkova (1964)	5	55-104	3.0-20	3.7	2.8-4.1
USSR SNIP II-3-79 (1979)	5	62-112	5.0,8.0	5.5	4.2-7.3
		Rotary Kiln Aggregates With Natural Sand			
Natsievski (1977)	6	70-100	5.5-6.0	5.8	5.2-6.1
Schule, et al (1976)	12	71-102	3.0-4.4	3.65	2.7-4.3
" " "	9	83-93	3.4-3.9	3.6	3.4-3.9
Schule & Kupke (1972)	1	111	2.8-11.7	4.9	4.4-5.4
" " "	3	87-100	2.5-4.8	4.2	2.3-5.5
USSR SNIP II-3-79 (1979)	3	50-75		6.0	5.5-6.5

*Hot wire test method.
**Multiply pcf values by 16.03 to convert to kg/m^3.

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TABLE 3.13 THERMAL CONDUCTIVITY MOISTURE FACTORS FOR CONCRETES CONTAINING VARIOUS NATURAL AGGREGATES.

Source	Aggregate	Density* pcf	Moisture Content, % by weight	Thermal Conductivity Moisture Factor, % Increase in Thermal Conductivity per 1% of Moisture	
				Mean	Range
Lentz & Monfore# (1965)	Calcareous	141	1.4	13.2	-
" " "	Sand & Gravel	"	4.3	10.2	-
Lentz & Monfore# (1966)	Marble	143	5.2	4.8	-
" " "	Limestone	126	1.0-9.8	5.2	-
" " "	Sandstone	120	3.1	16.1	-
" " "	"	"	11.7	8.5	-
Tyner (1946)	Limerock	106-113	5.0	5.3	4.6-5.9
Cammerer & Achtziger (1972)	Dolomitic	148-145[a]	4.0-4.3	10.5	9.5-12.4
" " "	Limestone	144.5[b]	4.3	5.5	4.4-6.5
Lewicki (1967)	Lightweight Limestone	69-100	4.5-8.0	3.9	1.3-5.6
USSR SNiP II-3-79 (1979) (standard values)	Gravel, Stone	150-156	2.0,3.0	7.3	7.7,6.3

*Multiply pcf values by 16.03 to convert to kg/m^3.
#Hot-wire test method for thermal conductivity.
[a]Cement content 305 to 538 pcy (181-319 kg/m^3).
[b]Cement content 734 pcy (435 kg/m^3).

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TABLE 3.14 THERMAL CONDUCTIVITY MOISTURE FACTORS FOR CLAY BRICKS

Material Identify	Source	Density* pcf	Moisture Content, % by Weight	Thermal Conductivity Moisture Factor, % Increase in Thermal Conductivity per 1% of Moisture Mean	Range
-	Krischer & Esdorn (1956)	82.4	0-7.6	14.2	linear
-	Kaufman (Neusikhin, et al	105.7	0-7.1	25.0	linear
	1965)	112.8	0-4.4	28.3	"
-	Paljak (1973)	100.0	7-15	7.4	8.6-6.1
	" "	87.4	7-15	6.9	7.7-6.0
Red Shale	Natl. Phys. Lab. (1948)	134.8	8.0	9.3	-
Sandstone Marl	" " " "	126.7	2.5	18.1	-
" "	" " " "	"	5.0-9.2	12.1	12.8-11.4
Clays	" " " "	124.2	8.0	9.5	-
Brick Earth	" " " "	122.3	2.0	9.8	-
" "	" " " "	"	5.5-14.0	11.2	12.9-10.8
Fletton	" " " "	101.7	4.3-19.0	5.3	6.3-4.6
Gault Clay	" " " "	107.3	2.5-22.5	5.7	6.8-5.0
London Stock	" " " "	86.7	2.5-5.0	26.5	29.2-23.8
" "	" " " "	"	11.0	14.3	-
	" " " "	"	20.0-34.0	10.2	11.2-9.5
-	Jespersen (1953)	119.2	1.6-2.6	29.2	32.8-25.6
-	" "	"	5.3	16.7	-
-	" "	104.8	1.8-6.0	13.6	15.4-11.0
-	" "	81.1	2.3-7.7	11.3	12.1-10.1
-	" "	78.6	2.4-4.0	18.2	19.6-17.0
-	" "	"	8.0	13.2	-
J-5 Solid	" "	87.4	2.2-3.3	9.4	9.9-8.8
" "	" "	"	7.2	6.2	-
J-5 Cored	" "	71.8	2.6	13.8	-
" "	" "	"	4.4	11.1	-
" "	" "	"	8.7	7.4	-
-	J.S. Cammerer** (1956)	122.0	0.7-1.7	20.2	21.0-18.3
-	" "	121.1	1.0-2.3	43.2	44.1-48.0
-	" "	113.0	1.4-3.4	24.9	23.2-26.6
-	" "	98.9	1.1-4.5	20.0	23.2-17.7
-	" "	106.7	1.4-4.1	6.5	7.5-5.2
-	" "	101.1	2.0-4.3	17.2	17.1-17.5
-	" "	98.0	0.7-3.8	18.0	22.3-14.5
-	" "	93.0	0.8-3.4	16.6	18.6-14.7
-	" "	91.1	3.0-5.8	15.8	15.5-16.2
-	Dimitrov (1965)	109.8	1.2-2.2	27.6	25.2-30.6
-	" "	"	5.2-6.8	17.7	-
-	" "	106.7	1.0-2.9	40.0	49.6-33.4
		"	4.4-8.7	20.0	-
Walls with cement-sand mortar	USSR SNiP II-3-79 (1979)	112.3	1.0,2.0	24	25.0,23.0

* Mutliply pcf values by 16.03 to convert to kg/m^3.

** Cammerer's thermal conductivity values for oven-dry samples used in the calculations are extrapolations by Valore from data given by Arnold (1969).

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4. CURRENT STATUS AND RECOMMENDATIONS FOR TESTING OF MASONRY MATERIALS

4.1 GENERAL PROBLEMS IN DETERMINING THE THERMAL CONDUCTIVITY OF MASONRY MATERIALS

Apparent Testing Problems

Apparent problems arise when different laboratories report markedly different thermal conductivity or thermal conductance test values for purportedly the same materials. This can occur when density of concrete, for example, is regarded as the sole unqualified criterion for estimating heat transfer properties, irrespective of differences in mineralogic or chemical composition of the materials tested. This type of problem is due to the use of a single density-thermal conductivity relationship such as that appearing in Chapter 23 of the ASHRAE Handbook of Fundamentals (1985). As a result, this is not a testing problem, but rather, it is an evaluation problem due to failure to take into account the specific thermal properties of the constituents of masonry materials. That density alone is not a sufficient thermal criterion for comparative evaluation is illustrated in the following examples. Two 100 pcf (1600 kg/m^3) concretes contain (a) 100 percent expanded slag and (b) a blend of expanded shale and quartzitic sand. Respective thermal conductivities of oven-dry concretes, based on Valore's empirical relationships are 3.1 and 5.3 Btu/h-ft^2-(F/in.) (0.45 and 0.76 W/m-K). The value for the concrete with the sand-expanded shale aggregate blend is about 70 percent higher than that for the expanded slag concrete, but both concretes are in the "lightweight" category in ASTM specifications for load-bearing concrete masonry units. A hypothetical, dry 100 pcf (1600 kg/m^3) concrete with 100 percent expanded shale aggregate would have a thermal conductivity of 4.05 Btu/h-ft^2-(F/in.), (0.58 W/m-K); however, masonry units with 100 percent of this type of aggregate rarely exceed 85 pcf (1360 kg/m^3) in dry bulk density in blocks produced in North America or Europe.

Thermal conductivity and thermal conductance test results obtained prior to 1970 have been sometimes regarded as less reliable than more recent data. One example is obtained in a 1977 letter from an official of a Canadian provincial ministry of "Consumer and Commercial Relations" to a provincial building officials association rejecting the use of "loose fill in block." The pertinent comments are:

> "We understand that some of the data published by NCMA (National Concrete Masonry Association) has been in question for a number of years. Results of tests on full scale block walls published by the National Bureau of Standards

indicates the thermal resistances of actual walls are only one-half of the published values. I was informed that some measurements and calculations had serious errors.

I am told that NCMA has since completed new tests....and that the thermal resistances were significantly below the published values."

Some of the apparent discrepancies alluded to are not difficult to identify. Two major university laboratories provided data prior to 1967: the Pennsylvania State University from 1952 to 1967 and the University of Minnesota (Rowley and Algren), in 1937. A major United States laboratory specializing in heat transfer testing has tested numerous concrete block walls since 1975, and has obtained different results. However, there were important differences in the composition of block concretes and in test conditions between the earlier and the later tests. The mean wall temperature in the earlier studies was 40 to 45 degrees F (4.4 to 7.2 deg. C), but averaged about 75 degrees F (25 deg. C) in the more recent tests. The more significant difference was that, in the earlier tests of 22 walls at the University of Minnesota and 24 at Pennsylvania State University, the block concretes contained only a single type of aggregate. Most of the walls were made with 100 percent lightweight aggregates and contained no supplementary normal weight natural aggregates. In the more recent post 1974 tests, 16 of the walls were made with expanded shale aggregate combined with normal weight natural sand.

Additional test results have been obtained since 1980 on all-lightweight aggregate and blended normal weight-lightweight aggregate concrete block walls. Valore's correlations for the International Masonry Institute (1988) show that the older and the more recent test results correlate equally well with calculated U-values when compositional differences among masonry unit concretes are taken into account. If there are differences due to laboratory techniques, they are not evident in the test results. This statement applies to block walls with insulated as well as noninsulated cores. In this context, laboratories are urged to ascertain the volumetric composition of aggregates in blocks in test walls, and the mineralogic type of normal weight natural aggregates used, either alone or in combination with lightweight aggregates of specific types.

Real Testing Problems

Faulty testing procedures have undoubtedly caused some of the large differences in thermal conductivity test results upon apparently similar materials reported in the literature. Tye and Spinney (1976) have discussed measurement problems in detail for rigid, heterogeneous materials such as concrete. The ASTM C177 test method is complex; under the best conditions, accuracy within +/- 5 percent can be attained for rigid, homogeneous specimens. Clearly, good results require testing by specialists. Specimen surfaces must be flat and parallel*. Accurate measurement of surface temperatures would appear to be a simple task but it becomes particularly demanding in the

testing of such heterogeneous materials as concrete and masonry. A thermocouple junction responds to temperature at a point. At least three potential sources of error exist: (a) point-to-point variations in temperature due to differences in thermal conductivity of the aggregate and cement paste binder components of concrete; (b) air-gaps between thermojunctions and specimen surfaces; and (c) errors in thermojunction temperature response due to conduction of heat away from specimen surface contact points by lead wire. In low-thermal conductivity materials this heat loss cannot readily be replenished. Problems (b) and (c) cause warm-face surface temperature values registered to be lower than the true temperature, resulting in underestimates of thermal conductivity. While (b) causes higher errors for higher-thermal conductivity specimens, (c) causes higher errors for lower-thermal conductivity specimens; nevertheless the errors are additive rather than compensatory. The use of a thin metal (copper) disc firmly adhered to a specimen surface with the thermojunction soldered to the disc and the first three or four inches of insulated lead wire in close contact with the disc satisfactorily minimizes all three types of errors by providing good contact and by providing an average temperature over an area, rather than at a point.

The magnitude of measuring errors due to small air gaps between temperature sensor and specimen surface is indicated by the following: Air-gaps averaging 0.001 inch (0.025 mm) between both specimen surfaces and thermal elements can cause thermal conductivity to be understated by up to 15 percent for a normal weight concrete specimen one inch (25 mm) thick, but only by about 2.5 percent for 2 inch thick specimens of a typical light weight aggregate concrete and by about 1 percent for similar specimens of insulating concretes. (Calculations are given in Appendix D.)

The degree of heterogeneity of a material further complicates the testing problem for high thermal conductivity materials. Concrete and bricks are homogeneous when considered in relatively thick sections. But concrete is a true composite usually consisting of 65 to 70 percent aggregate and of 30 to 35 percent hardened cement paste binder, by volume. Thermal conductivity of the aggregate can be 10 to 20 times that of the binder matrix, for masonry units and fully compacted normal weight concretes. Densities of normal weight

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* British Standard B5 874 requires that rigid materials be grounded thin to an accuracy of 0.2 mm (0.0079 in.). Thin sheets of silicone rubber between specimen and hot and cold plates are used to "ensure good thermal contact". (Loudon, 1979).

aggregates range from 160 to 170 pcf (2600 to 2700 kg/m^3); thermal conductivities depend on mineralogial composition and range from about 15 to 45 Btu/h-ft^2-(F/in) (2 to 6.5 W/m-K) for basalts, granites, limestones, and quartzites or their mixtures. Thermal conductivity of dry, hardened portland cement paste ranges from about 1.0 to 3.5 (0.14 to 0.5). The number and placement of thermocouples in testing such materials is critically important. In addition, the ratio of specimen thickness to coarse aggregate size affects results. Specimen size must therefore be large in relation to the particle size of aggregates. Rowley and Algren (1937) used two-inch (51 mm) thick hot-plate specimens and virtually all of the European studies since 1960 have tested specimens of similar thickness. Kluge et al (1949) and Price and Cordon (1949) employed specimens one-inch (25 mm) in thickness, which accounts, in part, for relatively high scatter in their data.

Variations in density are inevitable in composite masonry materials; and they occur from brick to brick, block to block and point to point within precast and cast in-situ concrete. These variations have been studied by Schule et al (1976), Loudon (1979), and in unpublished work by Valore (1958), for light weight concrete block and plastic concretes ranging in dry density from 30 to 100 lb/ft^3 (500 to 1600 kg/m^3). Coefficients of variation averaged 1.8% in Schule's work for precast concrete, and were 2.4 to 2.9% in Valore's study of concrete units. Loudon's values for concrete blocks in the UK varied more widely. Van Geem (November 1984) and Van Geem, et al (1982) gave densities of 42, 48, and 46 pcf (673, 770, and 735 kg/m^3) for nominally the same perlite concrete; our calculated range of thermal conductivities is +/-7.5 percent. An increase of 1 percent in density can cause a 3% increase in thermal conductivity for normal weight 140 lb/ft^3 (2240 kg/m^3) concrete, 1.6% for 80 lb/ft^3 (1280 kg/m^3) concrete and 1.1% for 40 lb/ft^3 (640 kg/m^3) concrete on the basis of ASHRAE Handbook of Fundamentals Chapter 23 (1985), Valore (1980), and other thermal conductivity-density relations. While density variation is separate from other thermal conductivity measurement problems, it seriously affects the usefulness of test data in calculating heat transfer characteristics of structures. What is required is the choice of representative units for testing to reflect average densities of parent batches of materials. While the averaging techniques described in the next section on refinements in testing can reduce variations in results for identical specimens, they cannot compensate for inevitable specimen-to-specimen differences. Here it is necessary to determine the proper number of tests for obtaining statistically valid estimates of thermal conductivity for parent populations. [See ASTM STP15D Manual on Presentation of Data, pp. 53 to 58 on "Limits of Uncertainty of an Observed Average", (1976), as a function of the number of tests and standard deviation (or coefficient of variation) of a group of replicate tests.] Basically, we are concerned with two aspects of thermal conductivity test results: variations due to testing techniques and statistical variations inherent in the materials themselves.

Development of accurate thermal conductivity data requires that

the variables enumerated above be properly considered. Errors due to lack of planeness of specimen surfaces can be minimized by testing specimens of a given material in different thicknesses to reduce boundary effects. The heterogeneity of the materials tested can also be considered. Attainment of statistical homogeneity can be approached by using specimens of sufficient thickness to minimize effects of aggregate size and aggregate-binder thermal conductivity mismatch. Because of these differences in thermal conductivity, a single test value may provide little information. Sufficient numbers of specimens of heterogeneous materials should be selected for testing to compensate for variations in density, and therefore, in thermal conductivity of parent materials. This in itself will tend to reduce the scatter in test results due to problems with heterogeneity of scale. The problem of larger heterogeneities of hollow blocks and bricks with complex web-core configurations is discussed in connection with guarded hot-box tests of masonry walls.

4.2 COMPARISON OF THERMAL CONDUCTIVITY VALUES FROM HOT-BOX AND HOT-PLATE TESTS OF CONCRETES

The following discussion covers details of thermal conductivity testing problems that relate to experimental techniques and illustrate, with examples from the literature, differences in results obtained when techniques are changed.

There is considerable disagreement between the results from test procedures widely used today, although it might be expected that different standard test methods for determining heat transmission properties of materials would yield essentially similar values for thermal conductivity in tests of the same material. Specifically, tests by the Guarded Hot Plate (ASTM C-177) and the Guarded Hot Box (ASTM C-236) of the same monolithic concrete, despite large differences in specimen size, ought to provide similar values for thermal conductivity.

Rowley and Algren (1937) tested monolithic carbonate sand-gravel concretes in three thicknesses: two inches (51 mm) by the guarded hot-plate and four inches (102 mm) and six inches (152 mm) by the guarded hot-box. None of the specimens was in an oven-dry condition when tested. Thermal conductivity values for specimens of comparable densities were 12 to 13 Btu/h-ft^2-(F/in) (1.7 to 1.9 W/m-K) for hot-plate tests (moisture content about 3.5 percent by weight), 15.5 Btu/h-ft^2-(F/in) (2.2 W/m-K) for 4-inch specimens and 14 Btu/h-ft^2-(F/in) (2.0 W/m K) for 6 inch specimens (moisture content about 2 percent by weight). Moisture contents of 4 inch specimens are unknown but were probably higher than for 2 inch specimens. The agreement is satisfactory. Greater cement paste concentration at surface boundaries, indicative of reduced density and thermal conductivity in the surface layers, would tend to give slightly lower thermal conductivity in thinner specimens. The two testing methods are in essential agreement.

A similar comparison for 78 pcf (1250 kg/m^3) expanded shale monolithic concrete of 2 inch hot-plate and 4 inch hot-box specimens

yielded virtually the same thermal conductivity values: 3.97 Btu/h-ft^2-(F/in) (0.57 W/m-K) for hot-plate specimens and 3.95 (0.57) for 4 inch hot-box specimens. The moisture content was 8.5 percent for hot-plate specimens and unknown for hot-box specimens. Our calculated thermal conductivity for a dry density of 78 pcf (1250 kg/m^3) and 8.5 percent moisture is 3.65, which is 7.7 percent lower than Rowley and Algren's values. Again, there is essential agreement.

Larson and Van Geem (1986) also compared hot-plate and hot-box thermal conductivity values for sand-gravel concretes with aggregates from the same source as those used by Rowley and Algren, and for expanded shale and expanded perlite concretes. The hot-box wall specimens contained 5/8 inch (16 mm) vertical and horizontal reinforcing steel bars spaced 12 inches (305 mm) on centers. The walls were 8.3 inches (211 mm) thick and the hot-plate specimens were 2 inches (51 mm) thick. The thermal conductivity value from the hot-box test was 9.8 Btu/h ft^2(F/in.), (1.4 W/m K) when corrected for 1.4 percent moisture. The hot-plate thermal conductivity value was 16.1 (2.3), or 65 percent higher than the hot-box value despite the presence of steel reinforcement in the wall specimen. (We shall refer to a hot-box test of this wall again in discussing the method of attachment of thermocouple junctions to wall surfaces.) For expanded shale structural concrete with dry density of 94 pcf (1500 Kg/m^3), the thermal conductivity from the hot-box wall test was 3.6 Btu/hr ft^2(F/in.) (0.52 W/m K) when corrected to the oven-dry condition. (Our calculated value based on density is 2.7 percent higher.) Van Geem's hot-plate (oven-dry) value was 4.5 Btu/h ft^2 (F/in) (0.65 W/m K), or 25 percent higher than the hot-box value. For perlite concrete with dry density of 42 to 48 pcf (three different density values are given for this concrete by Van Geem, 1984, and Van Geem, et al, 1982), the thermal conductivity value from the hot-box test, (corrected to the oven-dry condition by Valore) was 1.11 Btu/h-ft^2-(F/in) (0.16 W/m-K) and the hot-plate thermal conductivity value was 1.44 (0.21 W/m K), or 30 percent higher than the hot-box value. Our calculated thermal conductivity values were 1.19 to 1.41 Btu/h ft^2 (F/in) (0.17 to 0.20 W/m K), depending on which density value was used. Could differences in thermal conductivity of hot-plate and wall specimens have been due partially to marked density differences?

Davies and Ford (1981) compared hot-box and unguarded hot-plate thermal conductivity values for 4 inch thick solid "homogeneous" masonry walls laid up with an "air-tight epoxy resin bond of negligible thickness". Comparative thermal conductivity values in U.S. units are shown in Table 4.1, corrected to dry condition:

TABLE 4.1 THERMAL CONDUCTIVITIES OF U.S. CONCRETES BY HOT-PLATE, HOT-BOX AND CALCULATIONS (DAVIES AND FORD DATA, 1981)

Concrete Type or Material	Density, pcf Unit	Density, pcf Wall	Thermal Conductivity Btu/h ft^2 (F/in.) Hot-plate	Hot-box	Valore calc	Difference in Thermal Conductivity between Hot-box & Hot-plate
Autoclaved Aerated	42	40	0.91	1.04	1.06	+14%
Expanded Clay	74	72	2.28	1.94	2.38	-15%
Sand-Gravel	118	116	7.15	5.25	6.1	-27%
Clay Brick	(142)	133	-	4.95	5.8	-

Davies and Ford hot-box thermal conductivity values ranged from 14 percent higher to 27 percent lower than hot-plate values. Thermal conductivity values calculated by Valore (1987) with empirical equations were in reasonable agreement with hot-plate test values for dry expanded clay concretes. Cubic model calculated thermal conductivity for sand-gravel concrete was intermediate between hot-plate and hot-box test values. Davies and Ford presented no hot-plate data for clay bricks, but our empirical calculated thermal conductivity for bricks was 17 percent higher than the hot-box value. Since the standard error of our empirical equation for bricks was 13 percent, the difference of 17 percent is not a serious discrepancy. It is concluded that we ought to find out why the two methods result in different conductivities: one or both may be incorrect; certainly, both cannot be right.

4.3 SUGGESTED RESEARCH IN ASSESSING STATE OF CURRENT TESTING PROCEDURES

It is in order to determine the present state of the art of testing by conducting round-robin tests of concrete specimens, as was done in a study reported by Spooner (1980) in the UK. In that study 10 laboratories tested the same specimens of normal weight, expanded slag, and aerated (cellular) concretes by the hot-plate method. Coefficients of variation were 11.4 and 6.4 percent for expanded slag and cellular concretes, respectively. No data for normal weight concrete were reported because the laboratories were "dubious as to the validity of their results". This is unfortunate since the scatter in thermal conductivity values for normal weight concretes could be, in itself, a useful

statistic for evaluating the suitability of these test methods for this kind of material. It is suggested that a similar program be carried out in the U.S. possibly by including one or two selected laboratories in the UK, West Germany, or France.

Materials tested should include normal weight concrete, expanded shale, sanded expanded shale, scoria and pumice aggregate concretes, and cement-lime and masonry cement mortars. Specimens should be 2 inches (approximately 50 mm) thick. Both fully-compacted structural and block concretes should be tested. In the latter case, masonry units 2 by 8 by 16 inches (approximately 50 by 200 by 400 mm) can be made and glued together at edges to provide specimens 16 inches (400 mm) square, which can then be ground with surfaces plane and parallel. The recommended concretes encompass densities of 60 to 140 lb/cu.ft. (1000 to 2250 kg/m^3) and thermal conductivities of 2 to 14 $Btu/hr\text{-}ft^2\text{-}(F/in)$ i.e., 0.29 to 2.0 W/m-K. The normal weight concrete should include a highly quartzitic sand and gravel (e.g., Campbell's Maryland White Marsh material) and a commercial granitic or carbonate aggregate. Petrographic analysis should be performed on all aggregates to be used in the concretes.

There is an equal need for a round-robin program for masonry walls. Since concrete block walls cannot easily be transported, it is suggested that batches of blocks be ground, top and bottom, numbered, and dry-stacked to build walls with taped joints. Dry stacking eliminates lengthy "conditioning" times needed before testing mortared walls, and moisture contents of units can readily be determined; a skilled mason is not needed and different laboratories test the same blocks. A number of block plants have grinding facilities. As many as 5 or 6 laboratories, including one or two European laboratories, could participate in this study, which could be limited to three types of block concrete. European laboratories, i.e., those in West Germany, test smaller masonry walls than are tested in ASTM C236 guarded hot-box tests. The German standard DIN 52611 is based on the use of heat flow meter (HFM) for measuring heat flow. The metered area is 20 inches (500 mm) square. Proponents claim that DIN 52611 method is more reproducible than ASTM C236. Davies and Ford (1981) used both methods in tests of eight walls of masonry units: aerated, expanded clay, sand-gravel concretes, and clay bricks. Mean deviations between the methods for thermal conductance averaged less than three percent. Potential testing errors were given as +/-4.5 percent for hot-box and +/-7 percent for HFM results. The hot-plate and hot-box studies should be coordinated to the extent that concretes of the same materials and proportions used in the wall program be tested for thermal conductivity as well.

U-values obtained for dry-stacked walls could be converted to "practical" values by application of suitable correction factors for mortar and normal moisture. One objective of this work would be to bring thermal conductivity values from hot-plate and hot-box tests into agreement.

After completing such programs, the refinements for thermal conductivity testing could be applied in attempting to reduce the scatter of results, and to see if calculation of the thermal conductivities and U-values by the series-parallel method is viable for estimating heat losses. It has become necessary to develop accurate calculation procedures for estimating R and U-values of masonry walls because the costs of testing have so increased that it is not feasible to test walls of units of the wide variety of shapes and sizes now available for various building projects.

The simplest wall test is that of monolithic concrete. Testing walls of solid bricks or blocks is also relatively simple. Thermal conductivity values from hot-box tests of solid-block walls, as tested by Dynatech Scientific, and monolithic walls, as tested by Construction Technology Laboratories (Van Geem, 1984) are not in good agreement with hot-plate test values (differences over 40%) obtained in the same laboratories, even after moisture corrections are applied. Methods of correcting thermal conductivity values for moisture are given in Appendix E.

4.4 NUMBER AND LOCATION OF THERMOCOUPLE JUNCTIONS ON SURFACES OF HOT-BOX MASONRY WALL SPECIMENS

American Society for Testing and Materials "Standard Test Method for Steady-State Thermal Performance of Building Assemblies by Means of a Guarded Hot Box," C236-80 leaves certain details of the testing procedure to the discretion of laboratory personnel in charge of equipment design and test procedures. The ASTM method requires that the metered area of a wall test specimen should be large enough to be "representative" of walls in constructions. For concrete masonry walls of hollow units, this poses some difficulties with respect to placement of thermocouples over the face of the wall.

The metered area of masonry walls tested by one laboratory is 11.7 ft^2 (one m^2). For mortared walls of "regular" two-core 8 by 8 by 16 inch blocks, wall area fractions of mortar joint, concrete webs in the blocks, and hollow cores are 0.07, 0.21, and 0.72, respectively. In order for the various wall segments to be proportionately represented there should be one thermocouple over a mortar joint, three over webs in the blocks, and 10 over cores. For both vertical and horizontal joints to be proportionately represented, there should be one thermocouple over a vertical joint, two over horizontal joints, nine over webs and 30 over cores. The number of thermocouples (42) is therefore fast approaching practical limits.

How much difference does placement of thermocouples make in measured wall thermal conductance values? Ford and Lomax (1978) compared thermal conductance values obtained for aerated concrete block walls with six percent mortar wall area, with walls having "negligible" mortar area obtained by using an air tight seal of 0.2 inch (5 mm) compressed urethane foam instead of mortar. The

blocks were about 4 inches (100 mm) thick and had a density of about 38 pcf (600 Kg/m^3). Thermal conductivity of the blocks was 1.39 Btu/h-ft^2-(F/in.), (0.2 W/m-K) and that of the mortar was estimated as 8 (1.13). The thermal conductance of the mortared wall was 25 percent higher than that of the unmortared wall. In separate tests of mortared walls made with the same blocks, thermal conductance values were 20 percent higher for walls with all thermocouples placed on mortar joints than for walls with random placement of thermocouples. In this case the thermal conductivity value for the mortar was almost six times that for the blocks. Errors would decrease as the thermal conductivity of concrete approached that of the mortar. Nevertheless, errors could still be appreciable for walls of high thermal conductivity units or for walls of pumice, expanded slag or expanded clay units with thermal conductivity values about double that of the aerated concrete units.

Thermocouple placement utilized by three U.S. and Canada laboratories, A (US), B (US), and C (Canada), has been examined.

Laboratory A used 9 thermocouples over a one m^2 metered area in a large number of tests. One third were placed within 0.5 inch (13 mm) of vertical joints, one third were 0.5 inch (13 mm) from junctions of vertical and horizontal joints, and one third over concrete webs. None were placed over hollow cores.

Laboratory B used 24 thermocouples with 12.5 percent over vertical joints, none over horizontal joints, 33 percent over webs, and 54 percent over cores. This was more representative than the placement of thermocouples by laboratory A.

Laboratory C used 30 thermocouples; with 20 percent over vertical joints, 30 percent over horizontal joints, 20 percent over webs, and 30 percent over cores.

It is recommended that the effect of thermocouple placement be determined by testing. This can most readily be done by dry-stacking blocks with ground tops and bottoms to provide uniform dimensions. Comparison can be made with and without joints by using preformed sheet material to provide simulated mortar joints. One satisfactory material is "Wonderboard" expanded shale concrete board with a density of about 110 pcf (1800 Kg/m^3).

4.5 EFFECTS OF METHOD OF ATTACHMENT OF THERMOCOUPLES TO WALL SURFACES

The method of attachment of thermocouple junctions to specimen surfaces can have a pronounced effect on surface temperatures indicated in heat transmission tests of specimens of non-homogeneous materials, such as concrete hollow block walls. This is recognized in ASTM C-236 "Standard Test Method for Steady-State Thermal Performance of Building Assemblies by Means of a Guarded Hot Box". It is stated in paragraph 6.5.1.4: "With some non-homogeneous walls, such as concrete, it may be advisable to use copper shim stock under the thermocouples to average the temperature. Large aggregates in the concrete can create biased temperature readings". The method of attachment and the thickness and area of the shim stock are not specified.

Shim stock is available in thicknesses of 0.001 inch (0.025 mm) or greater. It should be attached to the specimen with a high thermal conductivity adhesive, such as quartz or metal powder-filled epoxy. Thermocouple junctions can be soldered to the shim stock. The area of the shim stock should have dimensions of three or more times the diameter of the largest aggregate particles. Finally, the metal should be covered with a thin opaque coating similar in emissivity to that of the specimen surface. It is of interest to note that, among three laboratories contacted, one laboratory occasionally uses a thin aluminum tab under thermocouples.

Discussion of details on the attachment of thermocouple junctions for measurement of surface temperatures in fire tests is given here to indicate a potential source of error in heat transfer tests at lower temperatures, such as hot-plate and hot-box tests. The "Temperature of the Unexposed Surface of Fire Resistance Test Specimens", by T.Z. Harmathy (ASTM Journal of Testing and Evaluation, Vol. 13, 1985, pp. 127-131) describes techniques used in the UK and North America for attachment of thermocouples for measuring surface temperature of fire test wall specimens. In the present ASTM standard E-119, surface thermocouples must be covered with asbestos pads about 0.4 inch (10 mm) thick with thermal conductivity 0.38 Btu/h-ft^2-(F/in), (0.055 W/m-K). Fire endurance end-point is defined as the elapsed time from the start of a test when the average unexposed surface temperature rises by 250 degrees F (139 degrees C). Harmathy has found that a 250 degrees F temperature rise indicated by the asbestos pad insulated thermocouples, as called for in ASTM E-119, is equivalent to a "true" surface temperature rise of 162 degrees F (90 degrees C). He recommends that surface thermocouples be simply adhered to specimen surfaces by means of adhesive tape without asbestos pads.

Davies and Ford (1981) tested walls of 4 inch (100 mm) thick solid masonry units bonded with epoxy adhesive of "negligible" thickness, and with conventional mortar. One side of each wall was coated with 0.24 inch (6 mm) of light weight plaster. For

each wall, tests were made with thermocouples on the plaster surface, and with thermocouples embedded in the plaster. After correcting for the resistance of the plaster (by Valore, by subtracting the R-value for 0.24 inch of plaster from the total R, using ASHRAE Chapter 23 R-values for light weight plaster) comparisons were made of effective thermal conductivity values obtained with surface and embedded thermocouples. For walls of aerated, expanded clay, and sand-gravel concretes, thermal conductivity values for surface and embedded thermocouples differed by an average of less than 2 percent (maximum individual difference of 7 percent). Thermal conductivity values were 1.06, 1.94, and 5.25 Btu/h-ft^2-(F/in.), (0.15, 0.28, and 0.76 W/m-K) respectively. For walls of fired clay bricks the effective thermal conductivity for embedded thermocouples was higher by 7 percent (epoxy bonded) and 23 percent (mortar bonded) than for walls with surface thermocouples. Without correcting for 0.24 inch of light weight plaster on the walls with surface thermocouples, differences were much larger (up to 43 percent higher for embedded thermocouples for the mortared brick wall). For this wall the thermal resistance of the thin plaster coat was about 20 percent of that for this brick. This shows that a thin semi-insulating coating over thermocouples cannot be neglected for specimens of relatively high thermal conductivity, but may have a small effect on results for low-thermal conductivity specimens.

More striking results were obtained by Larson and Van Geem (1986) in testing an 8.3 inch thick wall of a monolithic sand-gravel concrete (described earlier) in a calibrated hot box. Comparisons were made between effective thermal conductivities obtained by taping thermocouple junctions to wall surfaces with duct tape and by cementing thermocouples in grooves in wall surfaces with neat portland cement paste. Thermal conductivities were 9.8 Btu/h-ft^2-(F/in.) (1.41 W/m-K) for taped thermocouples and 14.3 (2.06) for embedded thermocouples, after correcting (by Valore) test values for moisture content; embedded thermocouple thermal conductivity values were 46 percent higher than taped thermocouple values. This difference was attributed by the authors to a thermal resistance for an air film between the taped thermocouple junction and the specimen surface of 0.26 hr-ft^2-F/Btu (0.046 m^2-K/W). This would indicate an air-gap thickness of 0.022 inch (0.56 mm) between thermocouple junctions and specimen surfaces. A quartz flour-filled epoxy adhesive of similar thickness would reduce this resistance by a factor of about 20. The contact (or lack of contact) resistance was about 45 percent of that obtained with embedded thermocouples for the concrete wall itself.

Expanded shale and expanded perlite monolithic concrete walls were not tested with embedded thermocouples. However, by subtracting the air-gap resistance obtained for the sand-gravel wall from R - values for expanded shale and expanded perlite walls obtained with taped thermocouples, estimated embedded

thermocouple thermal conductivity values are calculated to be about 17 percent and 5 percent higher than those obtained for uncorrected taped thermocouples, for expanded shale and perlite concrete walls, respectively. Curiously, calculated thermal conductivity values by the Cubic model equation for sand-gravel concrete and Valore's (1987) empirical values for expanded shale and perlite concretes, are in excellent agreement (mean deviation, calculation vs. test of 4 percent) with Larson and Van Geem's test and Valore's estimated embedded thermocouple values. This is probably fortuitous.

It appears that thermal conductivity values derived from Larson and Van Geem wall test data are high. First of all, the walls are reinforced with 0.625 inch (15.9 mm) diameter steel bars, spaced 12 inches (305 mm) on center, vertically and horizontally. This amounts to 0.6 percent steel, by volume, or 4 percent steel in the mid-thickness 1.25 inch layer. No correction of thermal conductivity for the steel has been indicated by the authors. The position and distribution of the steel bars would seem to warrant consideration of the intense lateral heat flow in the middle layer of the wall, which constitutes 15 percent of the wall thickness. The thermal conductivity values obtained for dry concretes by hot-plate and hot-wire tests reported by Larson and Van Geem (1986) and by Van Geem (November 1984) are also believed to be high.

As noted earlier, the thin metal averaging technique of Bittle and Taylor (1984), could also be applied to the hot-plate test to eliminate the practice of placing thermocouple junctions in grooves cut into specimen surfaces. The hot-wire test method is not believed by Saare and Jansson (1960) and Jonell (1960) to be sufficiently reproducible when used for testing concretes with dense or large aggregates.

The implications of the Construction Technology Laboratories studies by Van Geem, et al, and Larson and Van Geem, if corroborated in other laboratories, could have far-reaching consequences by bringing into question the validity of work done in many laboratories since 1960. The appreciable air-gap resistance they obtained between specimen surfaces and thermocouple junctions is especially disturbing in the light of Harmathy's recommendation to tape thermocouples to unexposed wall surfaces in fire tests. If two methods of attachment of thermocouples can show such large differences, what is the effect for hollow masonry walls?

Fortunately, differences decrease as the thermal conductivity of masonry materials decreases, and are further diluted for hollow masonry. The effects are diminished further in calculating total resistance by adding inside and outside surface resistances and resistances of any additional layers of material. Nevertheless, there is a measurement problem which can and ought to be rectified experimentally.

The use of neat cement paste of uncertain thermal conductivity for bonding thermocouples in grooves in specimen

surfaces is questioned. A better choice for a bonding cement would be an epoxy loaded with quartz or metal dust with thermal conductivity comparable to that of the concrete. A still better choice would be to follow the advice given in ASTM C-236, previously quoted, of soldering thermocouple junctions to copper (or brass) shim stock tightly bonded to concrete surfaces with a suitable thin glue line adhesive. ASTM C-236 does not specify bonding method or thickness or area of the shim stock, but 0.001 to 0.003 inch (0.025 t 0.076 mm) metal could be used for discs of 3 inch (76 mm) diameter. Individual dissimilar thermocouple wire ends could then be soldered to the metallic disc some distance apart to register average temperature over that distance.

4.6 POTENTIAL REFINEMENT OF THERMAL CONDUCTIVITY TEST METHODS

Innovative methods may be used to address problems with current testing techniques. It appears to be possible to reduce substantially the scatter in thermal conductivity test results for masonry materials such as clay bricks and concrete blocks by reducing or eliminating their inherent heterogeneities of scale. This has been done by Bittle and Taylor (1984) in measurements of thermal diffusivity of concrete-like composite specimens by averaging areas tested using a single thermocouple. A thin stainless steel plate was adhered to the face of a specimen with a high-thermal conductivity adhesive and ends of thermocouple wires were spot-welded to the plate, small distances apart. The steel plate is the electrical conductor ("intermediate metal") joining the two thermocouple wires and the temperature response is actually averaged over the distance between the welded ends of the wires. Further apparent modifications include the use of metallic foils such as steel, brass, copper and constantan. The latter two foils might be soldered together at mating edges or solder-laminated to form an "averaging" thermocouple. This technique could be applied to faces of hot-plate test specimens. Foils or "shim stock" 0.001 inch (0.25 mm) thick are readily available. Bittle and Taylor found that by increasing specimen thickness <u>or</u> by increasing the measured area the scatter in test results was greatly reduced. With their technique, thin hot-plate specimens might be satisfactory. It would then seem possible to test concrete block face-shells or segments of clay bricks without having to build up specimen thickness. Bittle and Taylor found that conventional individual thermocouples without the averaging plate provided high scatter in results, depending on whether the sensing junction was in contact with matrix or with a suspended particle. A general rule-of-thumb for casting concrete specimens for strength tests is that the smallest specimen dimension should be at least 3 to 4 times as large as the diameter of the largest aggregate particle, and that requirement should probably hold here.

An equally interesting procedure is that of Horai and Baldridge and colleagues (1969, 1971, 1972) for determining the

thermal conductivity of rocks by use of the needle probe (line heat source). The rock sample is pulverized to a grain size less than 0.004 in. (0.1 mm), or to pass ASTM No. 140 sieve, and mixed with water to form a slurry or paste. The thermal conductivity of the mixture is then determined with a needle probe. Knowing the thermal conductivity of water and mixture, the thermal conductivity of the rock particles is determined using the equation for the Maxwell model:

$$\lambda_c = \frac{v_s}{\dfrac{1}{\lambda_s - \lambda_m} + \dfrac{1 - v_s}{3\lambda_m}} + \lambda_m$$

where: v_s - volume fraction of solid
λ_s - thermal conductivity of solid
λ_m - " " " matrix
λ_c - " " " composite

The equation is calculated first in the normal manner and then by interchanging matrix and solid terms in the equation and replacing the term for volume fraction of the solid (i.e., particles), v_s by $1 - v_s$. The two values thus calculated are then averaged arithmetically. This procedure is termed "empirical" by the authors, and it yielded very good agreement with the cut-bar method normally used in tests of rocks. Valore has obtained good agreement with Kersten's (1969) tests of saturated soils in which a radial test method was used, by calculations based on the cubic Russell (1935) model without the necessity of reversing matrix and suspended particle roles.

The cubic model equation is:

$$\lambda_c = \lambda_m \left[\frac{v_s^{2/3}}{v_s^{2/3} - v_s + \dfrac{v_s}{\dfrac{\lambda_s v_s^{2/3}}{\lambda_m} + 1 - v_s^{2/3}}} \right]$$

The calculation then provides a theoretical rather than an empirical value. Cubic and Maxwell equations have been applied to calculations of thermal conductivity for dry autoclaved aerated (cellular) concretes by Valore using Horai's "normal-reverse" calculation procedure. Agreement of calculated values with the regression equation, based on 114 tests from 28 sources, was good. The regression equation is:

$Y = 0.13e^{0.33\,p^{0.5}}$ (U.S. units) where:
p = density in pcf
Y = thermal conductivity in Btu/h-ft^2-(F/in)
S_Y = 7.5% standard error,
n = 114
Coefficient of determination = r^2 = 0.93 (Valore 1987 IMI report).

Calculations had a mean bias of less than 4 percent, which was positive for the Cubic equation and negative for the Maxwell equation. The averaging of normal and reverse calculations was believed to be justified in this case since there are no distinct matrix and particulate phases, but rather "inter-penetrating networks." The thermal conductivity of air in the pores was taken as 0.173 Btu/h-ft^2-(F/in.) or 0.025 W/m-K and that of hydrated calcium silicate (pore-free) was extrapolated for its pore-free density of 2.6 g/cc, as 8.85 Btu/h-ft^2-(F/in.), (1.27 W/m-K).

The slurry-probe method cannot be used directly upon porous materials such as clay bricks and light weight aggregates since the pores would take up appreciable amounts of water, even in sand-size particles. However, thermal conductivity values could be obtained for pore-free powders of such materials, anchoring one end of the thermal conductivity-density curve, with the other end for zero density at the thermal conductivity of air, in the relationship Y: $ae^{b\sqrt{p}}$. In this case, y is the thermal conductivity of the powder, the intercept a is the thermal conductivity of dry air, 0.173 Btu/h-ft^2-(F/in.), (0.025 W/m K), e =2.718, and p is the density.

A modification of Horai's method is that used by Drozdov, et al (1981) in the USSR, in which the matrix "fluid" was dry quartz sand. Alternatively, small glass spheres, steel shot, zirconia sand, or aragonite sand could be used as the matrix material. The needle probe could then be used upon mixtures of the reference matrix particles and sand-size particles of the material to be tested. Drozdov, et al, applied their methods to low-density expanded clay particles and used, in addition to sand matrices, foamed polyurethane combined with expanded clay particles. In the latter case, values calculated by the Cubic equation averaged within 7 percent of test values.

The comparative cut-bar method is widely used for rocks and

refractory materials and can be applied to disc-shaped specimens about 0.25 in. thick by 1.9 in. diameter (6.5 by 48 mm) but particles of coarse aggregates are much smaller, typically of 0.19 to 0.75 in. (5 to 20 mm) diameter.

Among the methods described above, the needle probe appears to be the most versatile and, in the long run, the most economical in time because of the rapidity with which it can provide results. Therefore, it can provide the required volume of data needed for some of the heterogeneous materials considered here. It can be used for any range of moisture contents. Limitations with respect to the effects of boundary conditions at probe-specimen interfaces, as influenced by particle sizes in relation to probe diameter need to be established and correction factors determined.

Another rapid method is the surface comparator method of Rousan and Roy (1982), which gave thermal conductivity values about 60 percent too high for portland cement pastes and mortars, possibly due to rapid carbonation of surfaces, but which may be satisfactory for carbonation-free dry rocks and clay bricks. The screen-heater test method used by Yarbrough and Wilson (see Appendix C) is also a promising method of performing large numbers of tests at relatively low cost.

Finally, various versions of transient methods for determining thermal diffusivity, for its intrinsic value as well as for its use in calculating thermal conductivity, need to be re-evaluated. Bittle and Taylor concluded that diffusivity could be determined with their step-heating technique as accurately as with any other method. U.S. Army Corps of Engineers Methods of Test for Thermal Diffusivity of Concrete, CRD-C 36-73 (1973) and for Lightweight Insulating Concrete and Similar Materials, CRD-C 35-59 (1959) are examples of such transient methods.

4.7 EFFECT OF TEMPERATURE ON THERMAL CONDUCTIVITY OF MASONRY MATERIALS

Information on the effect of temperature on thermal conductivity of masonry and its constituents is scattered and, in some cases, contradictory. Very little study has been focused on the narrow temperature range of 0 to 160F (-18 to 71C) which encompasses temperatures of enclosing elements of buildings. Morgan and West (1980) found that thermal conductivity decreased with rising temperatures for 6 rocks of the U. S. Bureau of Mines Standard Rock Suite (quartzite, basalt, granodiorite, granite, limestone, and sandstone). These rocks or their mixtures form the bases for composition of normal weight aggregates. Harmathy (1970) found an increase and Harada (cited by Zoldners, 1980) a decrease of about 12 percent in thermal conductivity at 212F (100C) for cement pastes when compared with tests at room temperature. Harada's specimens apparently contained free moisture. Carman and Nelson (1921) found that the thermal conductivity of cement paste increased with temperature in the

122 to 390 F (50 to 200 C) range, by 16 percent.

Price and Cordon (1949) reported thermal conductivity data for 14 light weight aggregate concretes at mean temperatures of 27, 83, and 130 F (-3, 28, and 34C) with mixed results. Seven of the concretes showed little change in thermal conductivity with mean temperature; of the remainder, thermal conductivity values for four concretes increased and three concretes showed decreases with temperature rise. Variations were not systematic and may have been within the range of testing error.

Van Geem's (November 1984) hot-box tests of monolithic concrete walls showed no change in thermal conductivity for normal weight concrete and 4 percent increase in thermal conductivity for expanded shale concrete weighing 94 pcf (1505 Kg/m^3) when the mean test temperature was increased from about 35 to 100 F (2 to 38 C). The thermal conductivity for 42 pcf (675 Kg/m^3) perlite concrete increased 13 percent for a mean temperature rise from 53 to 100 F (12 to 38 C). Cammerer and Achtziger (1972) showed no change in thermal conductivity for monolithic dolomitic limestone concretes over a similar range of mean temperatures. Van Dusen and Finck's (1931) tests of solid clay brick walls at mean temperatures of 40 to 80 F (4.4 to 27 C) indicated an approximate average increase in thermal conductivity of about 4 percent in this temperature range. A general review by Barrett (1946) of thermal properties of refractory and other bricks indicates that the effect of temperature on thermal conductivity in the limited range of normal building exposures is quite small. It can be concluded, however, that the effects of variations in mean temperatures on the thermal conductivity of masonry materials, in this temperature range, has not received systematic study.

There are two aspects of the thermal conductivity temperature sensitivity that apply to masonry materials. The first is the effect of porosity (or of density) of the nominally solid portions of bricks, blocks, mortars and concretes whose density varies with the volumetric fraction of fine pores. The second aspect is the thermal conductivity temperature sensitivity of air-spaces formed during manufacture of hollow masonry units: cores or slots in large-core and multicore blocks and bricks.

In low-density quasisolid masonry materials, temperature sensitivity of air in pores predominates. The thermal conductivity of dry air (without radiation) increases by about 0.2 percent per degree F rise in mean temperature in the range -4 to 122 F (or 0.36 percent per degree C in the range -20 to 50 C) according to Krasnoshchekov and Sukomel (1977). For low-density perlite ceramics and concretes weighing 16 to 25 pcf (255 to 400 Kg/m^3) the thermal conductivity-temperature sensitivity factor is about 25 percent less than that of air, according to Gorlov (1976). As density increases, this factor decreases. It appears that the change in thermal conductivity with a change in mean temperature of 90 F (50 C) may be about 5 to 15 percent for light weight concretes of all types, and is probably negligible for

normal weight concretes.

The second aspect of the temperature sensitivity of the thermal conductivity of masonry applies to walls of hollow or cored masonry units, which encompass most of the masonry walls built today. Calculations of U-values of traditional North American large-core concrete block walls have been done by utilizing a "standard" thermal resistance of the core air-space of about 1.0 h-Ft^2-F/Btu (0.176 m - K/w) for thicknesses of blocks of 4 to 12 inches (100 to 300 mm). This value may be satisfactory for a mean temperature of 50 F (10 C). Use of this R value in series-parallel calculations of U-values of large-core masonry walls provides good agreement with test values (mean deviation of 6 percent for 51 tests, Valore 1987).

Anderson (1981) has demonstrated analytically that the R-value of small air-spaces (one inch or 25 mm thick or less) is affected appreciably by its horizontal length perpendicular to heat flow and his values are given as "standard" values in the British CIBS Guide (1980). Values larger than traditional R-values for air-spaces are given in the CIBS Guide for spaces of certain shapes. (See Appendix F for R-values).

Whether the core spaces are large, as in North American blocks, or small, as in European blocks, the resistances of these spaces are affected by mean temperature. This effect is not neglible, as shown in the ASHRAE Handbook of Fundamentals, Chapter 23, Table 2A (1985), listing the resistances of air-spaces. For spaces of 0.5 to 3.5 inches (13 to 90 mm) the resistance at a mean temperature of 50 F (10 C) is 17 to 20 percent higher than at a mean temperature of 90F (32C).

This increase is about double that due to the increase in thermal conductivity of air alone for this increase in temperature; the additional factor is a change in the radiation component of thermal conductance. From this, it can be seen that the temperature sensitivity of thermal conductance of hollow masonry is appreciably higher than that of solid materials having small pores.

Research on the thermal conductance or resistance of hollow cores or slots in masonry materials is strongly recommended. Size and shape of cores should be investigated over a range of practical mean temperatures. Such study should include masonry units with large cores of the sizes found in North American types of concrete blocks, as well as smaller cores that could be used in clay bricks. At the present time it is assumed that the cores in clay bricks become filled with mortar upon erection of walls. It is probable that some cores of smaller dimensions, i.e., less than 0.5 in. (13 mm) in diameter, in clay bricks would remain largely empty of mortar and would impede the flow of heat more efficiently than larger cores.

The resistance values for air-spaces in the ASHRAE Handbook of Fundamentals, Chapter 23 are based on the work of Robinson and Powlitch (1954). The ratios of length to thickness of their air-spaces ranged from 18 to 96; in effect, the air-space R-values of

Robinson and Powlitch, which form the basis for air-space R-values in most of the European codes, are for spaces infinitely large in length with respect to thickness. The most economical insulating "material" is air. It is urged that shape and size factors for R values of air-spaces in masonry be determined experimentally.

From these examples, it is clear that carefully organized research is needed to evaluate the temperature dependence of thermal conductivity of masonry materials. In particular air-spaces, portland cement pastes, mortars, bricks and light weight aggregates and concretes need to be studied. Morgan and West developed straight line relationships between thermal conductivity and reciprocal of absolute temperature for rocks; similar types of relationships for masonry materials could be developed.

4.8 DATA GAPS FOR MASONRY UNITS IN GENERAL

The effect of temperature on the thermal conductivity of concretes and fired clays needs further study within the -40F to 120F range. These data will verify the relationship between absolute temperature and thermal conductivity and will be useful in assessing the proper heat transfer rates through masonry walls in different climates. It would be proper to assign a lower U-value to a CMU wall in a cold climate (e.g. Montana) by comparison to the same wall in a hot climate (e.g. Florida).

The effect of moisture on the thermal conductivity of granular insulating fills is incompletely documented to date. New research should be undertaken on perlite, vermiculite, and expanded clay and shale fills.

There is a need for additional data on the fluctuation of moisture levels within masonry units when subjected to temporary exposure to water (rainfall). Correlations could be developed which will help establish climate-dependent practical thermal conductances (e.g. Phoenix, AZ versus Seattle, WA).

There are few data available on the magnitude of air infiltration through masonry walls and on convective loops within masonry walls. These data are needed to estimate the thermal behavior of masonry walls within a whole-building context.

4.9 DATA GAPS FOR CONCRETE MASONRY UNITS

Data on concretes containing scoria aggregate are too sparse to develop a meaningful relationship; it appears that some scorias may approach the relatively low thermal conductivity values, at a given density, usually attained by expanded slag concretes.

Information on the proper oven-drying regime for pumice concrete is also needed to avoid using temperatures so high and of such duration that a portion of combined water is removed from the aggregate in test specimens.

Data for sintered pelletized fly ash concrete are not adequate. European data on aerated (cellular) concretes show appreciably lower thermal conductivity values for those containing fly ash in place of quartz flour. With the growing use of fly ash for partial replacement of portland cement in masonry and structural concretes, decreases in thermal conductivity values are to be expected and should be quantified for both low-lime and high-lime fly ashes. This also applies to ground blast-furnace slag-portland cement blends. For testing such cementitious binders and aggregateless cellular concretes, the needle probe method may be satisfactory.

Data on concrete/polystyrene mixes are scarce and need to be supplemented.

Supplementary data for the relationship between moisture content and thermal conductivity is needed for concretes of all densities.

Independent tests for polystyrene inserts in concrete masonry units are required to better evaluate the thermal performance of these units and to devise more accurate methods for manual calculations of their U-values.

4.10 DATA GAPS FOR CLAY BRICKS

Very little thermal conductivity work has been done on clay bricks in this country except for that of Rowley and Algren in the 1930's. Unfortunately, their published studies do not include density values for the various bricks used in test walls. It can be shown that there is a definite thermal conductivity-density relationship for clay bricks tested in European programs, although there is some scatter in test results. In recent years most North American bricks have been of relatively high density, 125 to 150 pcf (2000 to 2400 kg/m^3) but that is beginning to change. Some American producers are now incorporating sawdust in clay mixtures to reduce density upon firing. Thermal conductivity tests in Europe have been done on bricks weighing well under 100 pcf (1600 kg/m^3). The U.S. brick industry is now aware of advantages of producing products with reduced thermal conductivity. Albert (1965) has studied the effect of diameter of hollow cores and fractional core volume on thermal resistance of "perforated" bricks. Austrian (Lang 1979) and West German literature (Mauerwerk-Kalender, 1984) show effects of size and shape of multiple cores on R-values of clay blocks. It is possible to estimate R-values using Valore's Modified Cubic model (IMI, 1987) for square cores (air-spaces) with axes perpendicular to heat flow, and Anderson's (1981) equation for estimating R-values of small cores as a function of their size and shape. (The Anderson equation is presented in Appendix F. The Modified Cubic Model is presented in Appendix G.) For some cores the R-values of the space within a core exceeds the conventional value of about 1.0 h-ft^2-F/Btu (0.176 m-K/W) by 50 percent. Using Anderson's values provides closer agreement of

series-parallel calculated and test R-values than conventional air-space R-values for multicore concrete blocks. Although Anderson's values appear in the British CIBS 1980 Guide, they ought to be verified independently to determine, in effect, the shape factor for R-values for various thickness to length ratios for cores of various sizes. Albert shows that, at equal core volumes, the smaller the core, the more effectively it increase the R-value of bricks. This should be no problem in brick manufacture where the extrusion process is predominantly used.

Thermal conductance of bricks with "frogs" and panels should also be assessed.

The variation of thermal conductivity in the longitudinal vs. transverse directions in bricks should also be studied, given the fact that due to the manufacturing process (commonly extrusion) the brick is not isotropic.

The cut-bar test method may be satisfactory for solid portions of clay bricks. It has been widely used for refractories in brick and other forms. If the building brick industry were to use the refractories industry methods, not only density, but chemical composition and firing temperature would be important areas of study for their effect on thermal conductivity.

4.11 DATA GAPS FOR MASONRY MORTARS

There are gaps in the extant literature on thermal conductivity of masonry mortars. In particular, there are insufficient data on sanded masonry mortars which are made with portland cement-lime binders in various proportions for different types of construction, or with masonry cement binders which usually consist of 1 to 1 blends of portland cement and pulverized limestone. The 1985 ASHRAE Handbook of Fundamentals lists a single value of thermal conductivity for a single density of "cement-mortar", which is not normally used as a masonry mortar in the U.S. Mortar thermal conductivity usually has a small effect on thermal conductance of large-core concrete block walls since mortar is applied only on the shells (U.S. practice), but can have a significant effect for brick, multicore, and solid unit masonry. At any rate, data are needed for mortars at densities that they have in the wall. Mortars that should be tested for thermal conductivity are: cement and cement-lime mortars corresponding to ASTM Specifications C270, "Mortar for Unit Masonry", and in particular the mortars of type M, S, N, O which vary in proportions of ingredients.

4.12 REPORTING REQUIREMENTS FOR TESTS SAMPLES

For the test data to be useful, test conditions and physical characteristics of test samples must be recorded and reported carefully. The following information should be provided on test samples:

(a) Concretes. Batch proportions of constituents: cement content, type and quantity of aggregates; for light weight and normal weight blends, the type, batch weights, moisture contents, and mineralogical type of natural aggregates are required. Yield of batches and oven-dry densities of masonry units and mortars, type of mortar; moisture contents of units from test walls immediately following tests; core configurations of units from mold dimensions.

(b) Clay Bricks. Oven-dry densities of solid portions of bricks, oven-dry densities of mortar; moisture contents of test walls immediately following tests; mortar joint thickness, dimensions of bricks and core configurations.

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5. STATISTICAL CHARACTERISTICS OF THE U.S. MASONRY BLOCK PRODUCTION

The main purpose of the survey was to characterize the bricks and blocks produced by the masonry industry in such a way that any national testing program developed as an outgrowth of this project be anchored in reality. Because the overall goal of improving the database on the thermophysical properties of masonry block products is to be able to upgrade properly the performance of the Nation's buildings, any testing undertaken to enhance and extend this database should concentrate on products commonly used, or which have the potential for high use in U.S. buildings. It should be noted in this context that the information assembled here provides only the present status of energy-related properties of masonry units, and that the U.S. masonry industry can significantly improve its products from a thermal standpoint. Consequently, although the concrete and fired clay bricks and blocks predominantly used today should continue to receive attention, thermally effective materials and geometric configurations, some of which are described in Chapter 4, should also be tested, given their potential for widespread use in the future.

5.1 INFORMATION SOLICITED BY THE SURVEY:

For concrete masonry products, the following information was solicited (see Appendix I for a copy of the survey form):

- Geographic areas of shipment
- Quantities of 8 x 8 x 16 in. equivalent block shipped.
- Characteristics of block by:
  - concrete density
  - block thickness
  - core
  - type of aggregate
- Use of insulating inserts.

A similar form was sent to brick manufacturers (see Appendix I) requesting the following data:

- Geographic areas of shipment
- Quantities shipped
- Characteristics of brick by

- brick size
- core size
- percentage of void
- use of panels, grooves and frogs
- compressive strength

The results of both surveys have been summarized and are presented here. They constitute the most comprehensive information source currently available on the masonry industry. (There are other data bases, including the proprietary NCMA surveys, which include information not available in this report, such as dollar value of sales. This type of information was not relevant to the current study and as a result it was not sought out.)

5.2 CONCRETE MASONRY UNITS

The survey on concrete masonry production for the National Concrete Masonry Association was sent to 498 concrete masonry plants as listed in the NCMA membership directory of 1986-87. These manufacturing plants are owned and operated by 300 member companies. The estimated total number of production plants (including NCMA members and non-members) at the time of the survey was 980.

As of September 15, 1987, 209 survey forms had been returned containing data for 248 manufacturing locations. This heavy response is remarkable for the CMU industry given the fact that NCMA surveys in 1986 and 1985 obtained data for 70 and 83 plants respectively (i.e. 28% and 35% respectively of this survey's data). The high rate of return on the SWA survey as compared to the two NCMA surveys may be due in part to the fact that the NCMA questionnaire requested, in addition to production data, confidential cost and financial information. Furthermore, the NCMA survey was handled by an independent accounting firm, the names of respondents were secret and no follow up was done. Steven Winter Associates, Inc. (SWA) followed up on all instances where a response was not initially obtained.

NCMA divides its membership into five geographic regions, based on similar markets and weather conditions (See Figure 5.1). Region I is composed of the Northeastern part of the US including West Virginia and Pennsylvania. Region II covers the South East extending West to the Mississippi. Region III is north of Region II and West of Region I, and extends West to the Mississippi. Region IV is West of the Mississippi and covers the Central Plain states, including Texas and Louisiana, to the Canadian border. Region V is the entire West including New Mexico, Colorado, Wyoming and Montana, as well as Hawaii and Alaska. NCMA has 94 member companies in Region I, 60 in II, 59 in III, 52 in IV, and 34 in V. The SWA survey received responses from 209 companies representing 248 plants: Region I - 47 replies, II - 51, III - 39, IV - 45, and V - 27.

Responses were received from all regions and contain data that is truly representative of all areas with the possible exception of

Hawaii. While no replies were received from Louisiana, Montana, North Dakota, South Dakota, West Virginia and Wyoming, it is felt that replies from adjacent states with similar markets and geography are representative of the type of blocks produced and used in these areas. Although replies received from the Northern half of California were also sparse, personal knowledge of the area and telephone communications with the Executive Director of the Concrete Masonry Association of California provided sufficient information relative to the type of concrete masonry used in the area.

The National Concrete Masonry Association sponsored surveys in 1985 and 1986 which covered, in part, some of the information requested in the "Assessment of Thermal and Physical Properties of Concrete Masonry Products" survey by Steven Winter Associates, Inc. The returns to September 15, 1987 are shown in Table 5.1.

TABLE 5.1 Comparison of Responses to NCMA and SWA Surveys

Survey	Total Plants	NCMA Member Plants	NCMA Member Companies	Total Plant Responses	Percent Responses of NCMA Member Plants
NCMA 1985	1011	550 +	366	83	15%
NCMA 1986	980	500 *	325	70	14%
SWA 1986/87	975	498 *	300	248	50%

+ Estimates
* Number of plants remained relatively constant due to buyouts and consolidation or companies.

5.2.1 AVERAGE PRODUCTION PER PLANT AND TOTAL U.S. PRODUCTION

Concrete masonry plants produce a wide variety of products in addition to those products used in exterior wall construction. These include interior partitions, load bearing interior walls, fire walls, sound absorbing and insulating walls, screen walls and fences, highway sound barriers, pavers, subgrade drainage structures, etc. The NCMA surveys for 1985 and 1986 contained the masonry unit production results stated as annual averages (based on 8 x 8 x 16 in. equivalents) per each plant. These production figures, as well as the figures obtained in the SWA survey, are listed in Table 5.2. The NCMA surveys categorize the blocks in (a) "standard", i.e., CMUs used in buildings for structural and non-structural applications, and which are generally covered by a finish; (b) "architectural", i.e., CMUs with higher compressive strength and lower absorption rates than the standard, designed to be visible and usually found in walls, such as split and fluted blocks; and (c) "others", i.e. CMUs not included in the above categories, such as pavers, chimney blocks and roof cap blocks. The SWA survey did not make this distinction, because it was

oriented solely toward obtaining data useful in determining the thermal properties of CMUs.

TABLE 5.2 AVERAGE ANNUAL PRODUCTION PER PLANT IN THOUSANDS OF EQUIVALENT 8 X 8 X 16 IN. CONCRETE MASONRY UNITS

	National	Region I	Region II	Region III	Region IV	Region V
1986 NCMA SURVEY						
Standard	3,222	4,094	3,836	2,877	2,390	3,238
Architectural	420	705	132	362	354	531
Others	372	309	309	333	198	387
TOTAL	4,014	5,108	4,278	3,572	2,942	4,156
1985 NCMA SURVEY						
Standard	2,804	3,669	4,460	2,349	1,680	3,087
Architectural	442	472	480	261	211	1,140
Others	235	262	151	209	145	525
TOTAL	3,482	4,404	5,092	2,819	2,035	4,752
1986/87 SWA SURVEY						
TOTAL	2,980	3,883	4,610	2,810	2,518	3,648

Since SWA survey had a considerably higher response rate than the NAHB 1985 and 1986 survey (3 and 3.5 times, respectively), its numbers are probably more reliable in extrapolating to the entire block production, by region and for the entire US.

The 1986/87 average production per plant can be used to provide a direct estimate of total production for all of the United States by multiplying the average production per plant in Table 5.2 by the total number of plants in Table 5.1. That number is: 2,980,000 x 975 = 2,905 million equivalent units, or approximately 3 billion equivalent units. Indirect estimates have been given traditionally by the masonry unit industry, based on total portland cement consumption or based on total mortar consumption. These estimates yield total masonry unit production at 3.5 to 4 billion concrete block equivalents and 7 to 9 million modular brick equivalents. It is the authors' opinion that indirect estimates are very rough, with an accuracy which probably no better than +/- 20 to 30 percent. The direct estimate of 3 billion equivalent CMUs is considered more accurate.

Although the SWA survey did not ask for a breakdown in end use, (i.e., standard/architectural/others) it can be reasonably assessed that the percentage of building versus non-building applications is

applicable to SWA totals. It is interesting to note in this context that approximately 10% of the blocks sold in 1986, and approximately 7% of the blocks sold in 1985, were consumed for use other than in buildings walls.

5.2.2 CMU PRODUCTION BY CONCRETE DENSITY

In addition to the overall quantity of blocks shipped, the SWA survey also requested information relating to the percentage of lightweight, medium weight, and normal weight blocks shipped. Light weight blocks are produced with lightweight concrete, which is defined as having a density lower than 105 pounds per cubic foot. Medium weight blocks use concrete with a density between 105-125 pcf and normal weight blocks use concrete with a density greater than 125 pcf. The NCMA surveys requested similar data except there were only two general categories: lightweight and normal weight. The exact weight per cu. ft. was not specified in the NCMA survey, making the results more difficult to assess.

The percentage of blocks sold in each category varies from region to region as well as from market to market. The use to which the blocks are to be put will also influence the type selected. Normal weight blocks are usually lower in cost because the aggregates are mined locally. The results of the SWA survey relative to block weight are presented in Table 5.3, expressed as a percentage of total units. NCMA survey results on light and normal weight block are also presented for comparison purposes.

TABLE 5.3 CMU PRODUCTION BY CONCRETE DENSITY IN PERCENTAGES

	National	Region I	Region II	Region III	Region IV	Region V
SWA 86/87						
Lightweight	28	16	33	20	38	28
Medium Weight	22	18	14	34	7	53
Normal Weight	50	66	53	46	55	19
SWA 86/87 with Lt. Wt. and Md. Wt. Consolidated						
Lightweight & Medium Weight	50	34	47	54	45	81
Normal Weight	50	66	53	46	55	19
NCMA 86						
Lightweight	49.0	27.2	83.6	28.5	52.9	73.1
Normal Weight	48.5	72.8	16.4	66.2	47.1	26.9
NCMA 85						
Lightweight	53.8	30.7	73.9	29.0	68.8	71.4
Normal Weight	45.0	64.3	26.1	71.0	33.2	28.6

The percentages are generally in good agreement at a national

level and in Regions I, IV and V, but differ in Regions II and III. This disparity appears to be generated by the participation of the major block producers in Regions II and III in the SWA survey, and not in the NCMA surveys. (By removing the block production of the largest manufacturers from the Regions II and III data, the SWA survey yields similar percentages to the NCMA surveys.) Furthermore, the NCMA questionnaire did not clearly define the lightweight block, giving the respondent leeway for interpretation. It is therefore concluded that the SWA survey is representative of the regional distribution of CMU's according to concrete density.

In summary, it can be stated that:

- Nation wide, the combined lightweight and medium weight block production is roughly equal to the normal weight block production.

- On a regional basis, normal weight blocks are produced in significantly larger quantities than the other blocks in Region I (approximately 65% normal weight); while light and medium weight blocks are prevalent in Region V (approximately 80% light and medium weight).

- Nation wide, the lightweight block production is slightly higher than the medium weight block production.

- On a regional basis, there is considerable variation. The ratio of lightweight blocks to medium weight blocks is 7 to 1 in Region IV, 2 to 1 in Region II, 1.5 to 1 in Region III, roughly equal in Region I, and 1 to 2 in Region V.

5.2.3 CMU PRODUCTION BY BLOCK THICKNESS

The SWA questionnaire asked for the percentage of blocks shipped by size. The results, expressed as percentages of 8 x 8 x 16 in. equivalent production, are presented in Table 5.4 below:

Table 5.4 CMU PRODUCTION BY BLOCK THICKNESS (Percentages)

	National	Region I	Region II	Region III	Region IV	Region V
>12 in.	0.08	0.01	0.00	0.06	0.47	0.00
12 "	20.61	30.40	14.92	21.27	23.42	12.34
10 "	1.95	5.43	0.34	2.07	1.27	0.10
8 "	57.33	44.91	69.35	51.97	49.17	66.77
6 "	8.46	7.38	6.51	11.85	7.47	12.33
4 "	9.62	10.75	8.60	12.30	8.39	8.46
< 4 "	0.40	0.96	0.25	0.47	0.06	0.01

Blocks thicker than 12 in. are seldom used, accounting for less than 0.1% of the total US equivalent block production. They are found sometimes in chimney, pilaster, and screen blocks. Concrete bricks and half-height slump blocks are produced in appreciable quantities in some regions. The range of 12 in. block shipped extended from a low of 12% (Region V) to a high of 30% (Region II). 12 in. block as a general rule is less than 1/3 of the production of an individual plant. Only 14 plants reported that they produced 40% or more 12 in. blocks. Most of the 12 in. thick blocks used in residential construction would be used in foundations. They would also be used in tall commercial or industrial buildings and they are frequently used either grouted or ungrouted in load bearing masonry construction.

In certain markets 10 in. thick walls are sometimes used in the same general applications as 12 in. walls. They are not available in all market areas and are not a major factor within the industry. The range is 0.1% to 5%, by region, and 2% nationally.

Eight inch blocks are the mainstay of the concrete masonry industry and they represent a US average of 57% of the production of all block plants. The range is 45% (Region I) to almost 70% (Region II). In only 9 plants in the survey 12 in. production was greater than 8 in. blocks - most of these plants were located in Minnesota and Wisconsin where there is an abundant supply of good, low-cost normal weight aggregate. Production and cost data are usually converted to 8 in. equivalents. When used in exterior walls they may be of lightweight, medium weight, or normal weight concrete. They may be single wythe or part of multiple wythe construction. They may be grouted and reinforced or non-reinforced. Generally speaking, when used as single wythe in architectural walls, they will be normal weight except in Southern California and the Arid Southwest.

The production of 6 in. blocks generally represents a small percentage of total US production (8%). The production varies by region between 7% to 12%. Six inch thick blocks are used in fence walls, as partitions, and sometimes as backup in composite or cavity walls, with other masonry material being used as the outer wythe.

Four inch blocks represent 10% of the US production (8% to 12% by region). They are used primarily in partitions and as a part of the exterior wall construction. When used as backup in either composite or cavity walls they would be lightweight. When 4 in. blocks are used in the exterior wythe as architectural veneer, they would be normal weight units in order to reduce rain penetration or to provide desired colors.

Two and three inch blocks represent less than 0.5% of US block production. These blocks are usually used as pavers, although 3 in. blocks are sometimes found in non-structural partitions.

In summary, it can be stated that:

- The 8 in. block is clearly the most prevalent, both nationally and at a regional level. It accounts for roughly half (57%) of the U.S. production and varies from

approximately 45% in Region I to approximately 70% in Region II.

- The 12 in. block is also significant nation wide, accounting for about 1/5th of the total production. Regional variation is significant. The 12 in. block accounts for 1/7th to 1/6th of the CMU production in Regions V and II (12% and 15% respectively), for roughly 1/5th of the CMU production in Regions III and IV (21% and 23% respectively) and for almost 1/3rd of all CMU production in Region I (31%).

- The 4 in. and 6 in. blocks account each for 1/10th of the U.S. CMU production (10% and 9% respectively).

  The regional variation is not significant.

- The 10 in. blocks account for 1/50th of U.S. CMU production (2%).

- Blocks thicker than 12 in. or thinner than 4 in. are manufactured in negligible quantities in all regions (less than 1/100th of the CMU production).

5.2.4 CMU PRODUCTION BY CORE CONFIGURATION

The SWA survey requested information relating to the percentage of blocks shipped by core configuration. Table 5.5 presents the percentage of solid, 2-core and 3-core configurations for each block size, by region and for the entire U.S.

TABLE 5.5 SOLID, 2-CORE AND 3-CORE CONFIGURATIONS FOR CMUS

12 in. Block	National	Region I	Region II	Region III	Region IV	Region V
Solid	2	4	3	1	0	0
2-Core	93	87	97	93	98	100
3-Core	5	9	0	7	2	0
	100%	100%	100%	100%	100%	100%

10 in. Block	National	Region I	Region II	Region III	Region IV	Region V
Solid	2	2	1	3	0	2
2-Core	89	85	99	90	100	98
3-Core	9	13	0	7	0	0
	100%	100%	100%	100%	100%	100%

8 in. Block	National	Region I	Region II	Region III	Region IV	Region V
Solid	3	6	3	4	2	1
2-Core	94	86	97	91	96	99
3-Core	2	8	0	5	2	0
	100%	100%	100%	100%	100%	100%

6 in. Block	National	Region I	Region II	Region III	Region IV	Region V
Solid	6	8	2	12	7	1
2-Core	90	63	95	76	88	99
3-Core	4	29	3	12	5	0
	100%	100%	100%	100%	100%	100%

4 in. Block	National	Region I	Region II	Region III	Region IV	Region V
Solid	24	28	30	25	13	13
2-Core	33	11	50	16	34	62
3-Core	43	61	20	59	53	25
	100%	100%	100%	100%	100%	100%

The percentages for 4 in. blocks should be regarded with caution, due to the small number of responses. Figures for blocks greater than 12 in. and smaller than 4 in. are not presented at all, because the number of responses obtained in the survey with regard to the breakdown of these blocks by core type is statistically insignificant.

The net or solid volumes of hollow concrete blocks are given in Table 5.6 based on block machine mold dimensions:

TABLE 5.6 SOLID VOLUME OF HOLLOW CONCRETE MASONRY UNITS

Size (Thickness)				Percentage of Solid Volume			
Nominal		Actual		Two-core		Three-core	
in.	(mm)	in.	(mm)	Standard	Range	Standard	Range
4	(102)	3.625	(92)	73	64-73	73	63-73
6	(152)	5.625	(143)	55	55-68	58	58-70
8	(203)	7.625	(194)	53	53-59	58	56-62
10	(254)	9.625	(244)	50	48-54	58	53-58
12	(305)	11.625	(285)	48	44-52	56	49-57

When the thermal conductivity of concrete block solids appreciably exceeds the effective conductivity of core spaces or core insulation, the webs of blocks can act as serious thermal bridges. Minimum web thicknesses are presently prescribed in ASTM Specification C-90 for "Hollow Load Bearing Concrete Masonry Units". Effective fractional web areas of standard units, in relation to total wall face area, range from about 0.20 for 4, 6, and 8 in. block walls, to 0.23 and 0.25 for 10 and 12 in. block walls, respectively. The purpose of the ASTM minimum web dimensions is to insure that the bending strength of the wall in the horizontal span will not fall below a value deemed necessary for resistance to wind loads. These requirements are based on old data, from tests of older types of units. Some second generation preinsulated blocks have fractional web areas that are reduced by about 40 percent from those of standard hollow units. This decrease in fractional web area, in turn, can substantially decrease the U-value of the wall. For example, the U-value of a wall made of 8 in. expanded shale concrete blocks with fractional web area reduced by 40 percent is 25 to 40 percent lower than the U-value of a similar wall of standard units with similar insulation. Various building codes require that bending strengths of walls of units with web thicknesses reduced from those required by ASTM Specification C-90 be determined by test according to ASTM E-72, Standard Methods of "Conducting Strength Tests of Panels for Building Construction." Walls of some second generation units have met these requirements.

As this discussion illustrates, alteration of CMU core configurations performed with the purpose of enhancing the thermal performance of CMU walls must satisfy certain requirements for the

structural integrity of such walls. This is another potentially fruitful area for research in which the structural performance of thermally efficient masonry walls would be evaluated in a comprehensive and systematic manner.

Finally, it should be noted that although masonry mortar has usually a higher thermal conductivity than low density concretes, mortar bedding does not have an appreciable impact on the U-value of U.S. lightweight CMUs. This is because in erecting walls of hollow blocks it is standard U.S. practice* to bed only face shells of blocks in mortar.

In summary, it can be stated that:

- Nationally, the 2-core configuration is overwhelmingly prevalent in 6 in., 8 in., 10 in. and 12 in. blocks, ranging from 90% to 100% of CMU production in these widths.

  The 2-core configurations is also well represented in 4 in. blocks, accounting for about 1/3rd of the 4 in.block U.S. production.

- Regionally, the 2-core configuration ranges form 85% to 100% for 6 in., 8 in., 10 in. and 12 in. CMUs, not a significant variation. The only exception is for Regions I and III, where 2-core 6 in. CMUs account for only 65% and 75% respectively of the 6 in. CMU production. However, given the relatively small number of responses indicating the breakdown of 6 in. CMU block production by core type, it is possible that the lower numbers are due to statistical inaccuracies.

- The 3-core configuration is prevalent in 4 in. blocks. The 3-core configuration accounts for 5% of all 12 in. block production, almost 10% of all 10 in. block production, and for less than 5% of the 8 in. and 6 in. block production.

  The data obtained by Steven Winter Associates, Inc. on the 3-core configuration are too scarce to support a regional distribution analysis.

- The solid block represents almost 25% of the U.S. 4 in. block production. It accounts for less than 5% of all other block thicknesses.

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* When two-core blocks are laid in running bond, which is the usual method, the webs of units in contiguous courses are not aligned and cannot effectively be bonded with mortar. Two-core blocks account for over 90% of total production of hollow CMUs, except for 4 in. thick units.

The data obtained by Steven Winter Associates, Inc. on the solid block configuration are too scarce to support a regional distribution analysis. However, it should be noted that appreciably quantities of solid concrete bricks and split and slump blocks are produced in some regions.

5.2.5 CONCRETE BLOCK AGGREGATES

The composition of aggregate, as obtained in the survey, is reported in Table 5.7 below:

TABLE 5.7 MINERALOGIC COMPOSITION OF AGGREGATES

Aggregate	Number of Plants	Percentage of Plants Surveyed
Calcitic and Dolomitic Limestones	63	30
Expanded Shales, Clays and Slates	58	28
Sand and Gravel	58	28
Pumice	20	10
Scoria	19	9
Expanded, Slag and Bottom Ash	15	7

The mineralogic types of aggregates most used in the production of U.S. concrete masonry units can be categorized as follows:

Normal Weight Aggregates
Sand and Gravel (quartzitic, carbonate, granitic).
Limestone (calcitic, dolomitic).
Granite and Trap Rock in minor quantities.

Intermediate Weight Aggregate
Oolitic Limestone (mainly in Florida)
Air-Cooled Blast Furnace Slag
Power Plant Bottom Ash or Cinder (from coal)

Lightweight Aggregates
Expanded shale, clay and slate (predominantly rotary kiln; some sinter)
Pumice (domestic and imported)
Expanded Blast Furnace Slag
Scoria (volcanic cinders, volcanic slag).
"Red Dog" (spontaneously burned colliery shale).

Normal weight aggregates are of natural origin. The particles have a bulk specific gravity of 2.6 to 2.7 (solid bulk density of 162 to 168 pcf). For calculation purposes the dry loose density is

assumed to be 100 pcf (1600 kg/m^3).

"Intermediate weight aggregates" is not a standard term but is used here to denote material which may be used as the sole aggregate or with additions of normal weight or lightweight aggregates to yield concrete blocks with net dry densities of 105 to 125 pcf (1685 to 2000 kg/m^3).

Lightweight aggregates of any mineralogic type are those meeting the loose, dry bulk density requirements of ASTM Standard Specification C331 "Lightweight Aggregates for Concrete Masonry Units." Maximum densities for these aggregates are 70, 55, and 65 pcf (1120, 880, and 1040 kg/m^3) for fine, coarse, and combined fine and coarse aggregate, respectively. There are no minimum limits for lightweight aggregate density. In general, fine aggregates are those passing the No. 4 sieve (0.19 in. or 4.8 mm.) but are frequently of smaller top size. Although a top size of 0.5 in. (12.5 mm) is permitted for coarse aggregates, consideration of small web thickness and preferred surface texture of hollow blocks generally limit the maximum particle sizes to those passing the 0.375 or 0.25 in. (9.5 or 6.4 mm) sieves. The use of all fines gradations has proved to be advantageous for some producers of concrete blocks, allowing attainment of consistent surface textures. The finest fractions, i.e. the "dust" fractions, are "pozzolanic", that is, they react with lime released by hydration of portland cements. (Reactions are accelerated during steam curing to enhance strength development.) Slag fines may be considered to be cementitious and also contribute to strength development during steam curing. All block plants in the United States use elevated temperature curing of some sort.

Concrete block production in the United States for the years 1984-1985 is estimated at 3 to 4 billion eight-inch hollow core equivalents per year. According to the SWA survey, one half of that production was in normal weight concrete units, and approximately one-fourth in intermediate weight, and one-fourth in lightweight concrete units.

The U.S. Bureau of Mines 1985 "Minerals Yearbook," Vol. 1, lists the annual consumption of lightweight aggregates by the U.S. block industry for 1984-85 in short tons as follows:

	Short Tons Used (Millions)	
Type	Concrete Block	Structural Concrete
Expanded Shale, Clay, Slate	2.65	1.30
Pumice (domestic and imported)	0.77	-
Expanded Slag	0.23	-
Totals	3.65	1.30

The Bureau of Mines tonnages are low since scoria and bottom ash (or cinders) are not listed. Furthermore, expanded shale or clay tonnage may also be low by as much as 15 percent, since industry figures for expanded shale, clay, and slate aggregate production are

about five million short tons, about 60 percent of which is supplied to the concrete masonry industry. Adding the amounts for pumice, expanded slag, and scoria used in lightweight concrete blocks having densities less than 105 pcf brings the total amount to about 4 million tons.

Aggregate consumption can be used to estimate block production and vice versa by use of "yield" factors for converting aggregate tonnage to net volume of hollow two-core 8 x 8 x 16 in. equivalent concrete blocks. About 1.22 +/- 0.7 cu. yd. of dry, loose aggregate are required to yield one cu. yd. of block concrete, which is the net volume of about 98 equivalent two-core blocks, for lightweight or blends of lightweight and normal weight aggregates. Normal weight aggregates are considered to average 100 pcf in dry, loose form. Expanded shale, clay and slate aggregates range in dry, loose bulk density from 40 to 60 pcf (average of 50 pcf). Densities of pumice are 40 and 50 pcf for domestic and imported types, respectively. Expanded blast furnace slag and scoria have an estimated average density of 60 pcf. These dry, loose bulk densities were used to convert the production tonnages of 1984-85 to loose volumes (Table 5.8):

TABLE 5.8 ESTIMATED LIGHTWEIGHT AGGREGATE CONSUMPTION FOR LIGHTWEIGHT CMU

Type	Dry, Loose Density (pcf)	Bureau of Mines Short Tons (Thousands)	Estimated* Cubic Yards (Thousands)	Cu. Yd. per 8 in. Block (100 pcf)	Total Block Equivalent (Millions)
Expanded Shale Clay, and Slate	50	2650	3926	0.0073	538
Pumice:					
Domestic	40	505	935	0.0060	156
Imported	50	260	480	0.0073	69
Expanded Slag	60	229	283	0.0119	24
Other**	60	250	309	0.0119	26
Total	-	3894	5933	-	813

* Authors' estimates based on average bulk, dry, loose densities of aggregate and average density of lightweight block concrete of 100 pcf (1600 kg/m^3).

** Scoria, bottom ash, "red dog", etc.

The 813 million lightweight block equivalents indicate a figure of about 3 billion total block production, which is in agreement with SWA's survey results (see 5.2.1).

5.2.6 INSULATION INSERTS

Preinsulated blocks with insulating inserts were used in all regions, with approximately 70% of all plants offering some type of core insulation. However, the total quantity amounts probably to slightly less than one percent of total U.S. production. 44% of all plants use Korfil, 7% Insulblock, 4% Thermobloc, 4% Flexitherm and 4% Blockfil. (All of the above are trade names for polystyrene inserts.) 5% of the producers simply indicated polystyrene and 0.5% polyisocyanurate.

5.2.7 CONCLUSIONS ON CMU PRODUCTION

The results obtained in the SWA survey (and corroborated against the NCMA surveys) allow us to define the most prevalent characteristics of the U.S. produced CMUs.

Concrete density: Refer to Table 5.3

A series of blocks representative of the U.S. production has the following distribution of concrete densities:

a) 50% with a density above 125 pcf
b) 20-25% with a density between 105 pcf and 125 pcf
c) 25-30% with a density below 105 pcf

Block Thickness: Refer to Table 5.4
A series of 8 x 8 x 16 in. equivalent blocks representative of U.S. production should have the following distribution of CMU widths:

a) 57% 8 in. CMUs
b) 21% 12 in. CMUs
c) 10% 4 in. CMUs
d) 9% 6 in. CMUs
e) 2% 10 in. CMUs
f) 1% CMUs wider than 12 in. and narrower than 4 in.

However, 6 in. CMUs are usually not used in the building envelope. Furthermore, CMUs wider than 12 in. and narrower than 4 in. are also rarely used in the building envelope, and are produced in very small quantities. Consequently, the series can be reduced to 8 in., 12 in. and 4 in. CMUs.

a) 65% 8 in. CMUs
b) 23% 12 in. CMUs
c) 10% 4 in. CMUs
d) 2% 10 in. CMUs

If the 10 in. CMU production is also considered insignificant,

the series becomes approximately:

a) 65% 8 in. CMUs
b) 25% 12 in. CMUs
c) 10% 4 in. CMUs

Cores: Refer to Table 5.5

A series of blocks representative of U.S. production should have the following distribution of number of cores:

a) 90-95% 2-core blocks for 12 in., 10 in., 8 in. and 6 in. CMUs
b) 5-10% 3-core and solid blocks for 12 in., 10 in., 8 in. and 6 in. CMUs
c) 33% 2-core blocks for 4 in. CMUs
d) 67% 3-core and solid blocks for 4 in. CMUs. If differentiation is desired, 3-core 4 in. CMUs can be considered to be roughly twice as many as solid 4 in. CMUs.

Aggregate: Refer to Table 5.8
The following aggregates are predominantly used in U.S. CMU plants:

<u>Normal Weight Aggregates</u>
Sand and Gravel (quartzitic, carbonate, granitic).
Limestone (calcitic, dolomitic).
Granite and Trap Rock in minor quantities.

<u>Intermediate Weight Aggregate</u>
Oolitic Limestone (mainly in Florida)
Air-Cooled Blast Furnace Slag
Power Plant Bottom Ash or Cinder (from coal)

<u>Lightweight Aggregates</u>
Expanded shale, clay and slate (mostly rotary kiln, some sintered)
Pumice
Expanded Blast Furnace Slag
Scoria (volcanic cinders, volcanic slag).
"Red Dog" (spontaneously burned colliery shale).

Insulation Inserts: Refer to page 5.15
70% of all plants surveyed reported that they offer rigid insulation inserts. The brand names of these inserts are provided below.

a) 44% of all plants offer Korfil
b) 7% of all plants offer Insulblock

c) 4% of all plants offer Thermobloc
d) 4% of all plants offer Flexitherm
e) 4% of all plants offer Blockfil

It should be noted that the production of blocks with inserts is about 1% of the total U.S. block production.

5.3 BRICK MASONRY UNITS

Steven Winter Associates, Inc. (SWA) simultaneously conducted a survey of brick manufacturers in the US, focusing on the members of the Brick Institute of America (BIA) and of the Western States Clay Products Association. The 42 survey responses are mostly from BIA members (35 responses, representing 46% of the BIA US membership of 81 companies). While there are no detailed available data from other similar surveys to assess the significance of these results in a thorough manner, some conclusions can nonetheless be drawn by comparing SWA's results to figures published by the Bureau of Census of the U.S. Department of Commerce. It appears that the SWA survey had a good response rate, from participants distributed across the entire US. As a result, conclusions drawn from this survey should be regarded as reasonably representative for the US brick production.

5.3.1 MOST COMMON BRICK SIZES

According to this survey, the five most common brick sizes are (Table 5.9):

TABLE 5.9 MOST COMMON BRICK SIZES (IN INCHES)

No	Brick Name	Height	Width	Length	# of Plants	% of Plants Responding to Survey
1	Standard modular	2-1/4	3-5/8	7-5/8	20	42
2	Standard non-modular	2-1/4	3-5/8	8	7	17
3	Oversize non-modular	2-3/4	3-5/8	8	3	7
4	Engineer modular	2-3/4	3-5/8	7-5/8	6	17
5	Utility/Jumbo modular	3-5/8	3-5/8	11-5/8	6	17

Of the 5-most-common brick group, the brick with 2-1/4 in. height, 3-5/8 in. width and either 7-5/8 in. or 8 in. length (standard brick, modular and non-modular) is by far the most common, being produced in large quantities by 55% of all plants (23 plants). Next is the brick with 2-3/4 in. height, 3-5/8 in. width and either 7-5/8 in. or 8 in. length (Oversize non-modular and Engineer modular respectively), which is predominantly produced by 21% of all plants (9 plants in the SWA survey). The larger 3-5/8 x 3-5/8 x 11-5/8 in. brick (either Utility

or Jumbo modular) is predominantly produced by 17% of all plants (6 plants in the survey).

5.3.2 CORE TYPES

Bricks with 75 to 100 percent net area (25 to zero percent coring) are nominally solid. Hollow bricks with more than 25 to a maximum of 40 percent coring are classified as hollow bricks. For clay units with more than 40 percent of coring, ASTM Specifications C212 for "Structural Clay Facing Tile" may be applicable.

Nominally solid bricks may contain coring of up to 25 percent by volume (a minimum of 75 percent solid in every horizontal plane). These cores are assumed to be filled with mortar during erection of a wall. For the great majority of brick plants in the survey, round core diameter in the survey ranged from 0.75 to 1.88 in. (19 to 48 mm). Rectangular or oval cores were offered with a thickness of 0.75 in. to 1.75 in. Only three plants used cores smaller than one in. (25 mm) in diameter.

Since cores of common size are virtually or completely filled with mortar, and since the thermal conductivity of mortar will usually not be greatly different from that of the solid portion of extruded bricks, it can be stated that in general cores do not modify appreciably the thermal resistance of bricks. Consequently, cored bricks may be treated as 100 percent solid units with respect to heat transfer. Coring is used by the brick industry because it promotes more uniform burning throughout a brick, thereby increasing strength, and it reduces materials requirements, unit weights, and transportation costs. However, there would be an advantage in using smaller round or rectangular cores of approximately 0.5 or 0.4 in. (13 or 10 mm) diameter or thickness, because "fat" mortars would not fill them. As a result, the small cores would provide thermally resistant air spaces, with effective thermal conductivities significantly lower than those of the larger cores. (See Appendix F Table on thermal resistance of air spaces taken from UK CIBS Guide of 1980, based on the work of Anderson, 1980). Unfortunately, not all raw clay or shale mixtures have suitable plasticity for extrusion through small-core dies and only 5% of factories offer bricks with 0.5 in. cores.

The SWA survey also inquired about the percentage of cores in the 5-most-produced brick types. 90% of these bricks are nominally solid, with coring of 25% or less. 10% of these bricks are classified as hollow with, with coring more than 25%.

5.3.3 COMPRESSIVE STRENGTH IN BRICKS

Approximately 80% of clay bricks used in buildings today are extruded, and wire cut. About 18% of the bricks produced are molded and approximately 2% pressed. All bricks are burned in kilns. Ninety five percent of all burning is done in tunnel kilns, while 5% takes

place in periodic kilns, in order to create special color and/or texture.

Most U.S. bricks meet the requirements of ASTM C216-85a for face brick. The Southwest and Los Angeles areas still have available bricks which meet ASTM C62 specifications (same physical properties as ASTM C216-85a).

Manufacturers were asked to indicate the compressive strength of five of their most widely produced bricks. The results are listed in Table 5.10 below:

TABLE 5.10 DISTRIBUTION OF COMPRESSIVE STRENGTH OF THE 5 MOST PRODUCED BRICKS

Restrained Compressive Strength psi	Percentage of Plants
Below 8,000	27
8,000 to 9,000	75
9,000 to 10,000	25
10,000 to 15,000	40
Above 15,000	1

Table 5.10 shows that the average compressive strength of extruded brick burned in a tunnel kiln in the U.S.. is between 8,000 to 10,000 psi. The bricks below 8,000 psi are usually molded or pressed, and/or are made with shale-type clays. Bricks with compressive strengths above 15,000 psi are usually made of fire clay, such as in the Ohio area.

5.3.4 PANELS, GROOVES AND FROGS IN BLOCKS

Bricks manufacturers were questioned on the type and frequency of imprints in their bricks. Panel, grooves and "frogs" are not common. "Frogs" are done for molded bricks and are therefore least common of all brick imprints.

5.3.5 CONCLUSIONS FOR BRICKS

The results obtained in the SWA survey allow to define the characteristics of the most prevalent U.S. produced bricks. These characteristics can be used to select statistically representative bricks used in buildings, when initiating thermal properties testing programs.

Definitions:	Standard modular	2-1/4 in. height, 3-5/8 in. width, 7-5/8 in. length
	Standard non-modular	2-1/4 in. height, 3-5/8 in. width, 8 in. length
	Oversize non-modular	2-3/4 in. height, 3-5/8 in. width, 8 in. length

Engineer modular	2-3/4 in. height, 3-5/8 in. width, 7-5/8 in. length
Utility or Jumbo modular	3-5/8 in. height, 3-5/8 in. width, 11-5/8 in. length

Size: Refer to Table 5.9

The bricks produced by most plants are:

a) Standard modular produced by 42% of all plants
b) Standard non-modular, Engineer modular, Utility/Jumbo modular, each produced by 17% of all plants
c) Oversize non-modular, produced by 7% of all plants

Cores: Refer to page 5.19

Ninety five percent of all plants use cores one inch or larger in at least one horizontal dimension.

Ninety percent of the 5-most-common bricks are nominally solid, with coring of 25% or less.

Ten percent of the 5-most-common bricks are classified as hollow, with coring more than 25%.

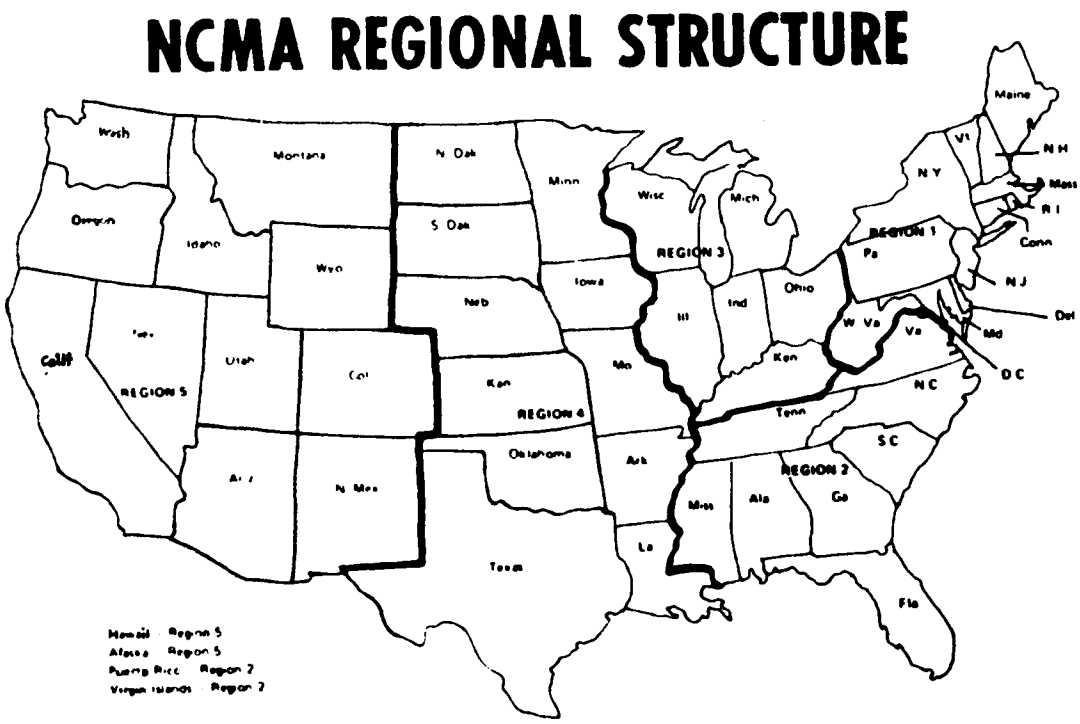
Compressive Strength: Refer to Table 5.10

The plants producing the 5 brick types are distributed according to the compressive strength as follows:

a) Roughly 25% of these plants produce bricks under 8,000 psi
b) 75% of these plants produce bricks in the 8,000 to 9,000 psi range
c) Roughly 25% of these plants produce bricks between 9,000 to 10,000 psi
d) 40% of these plants produce bricks with 10,000 to 15,000 psi
e) A negligible number of plants produce bricks with compressive strength in excess of 15,000 psi

FIG. 5.1

NCMA REGIONAL STRUCTURE



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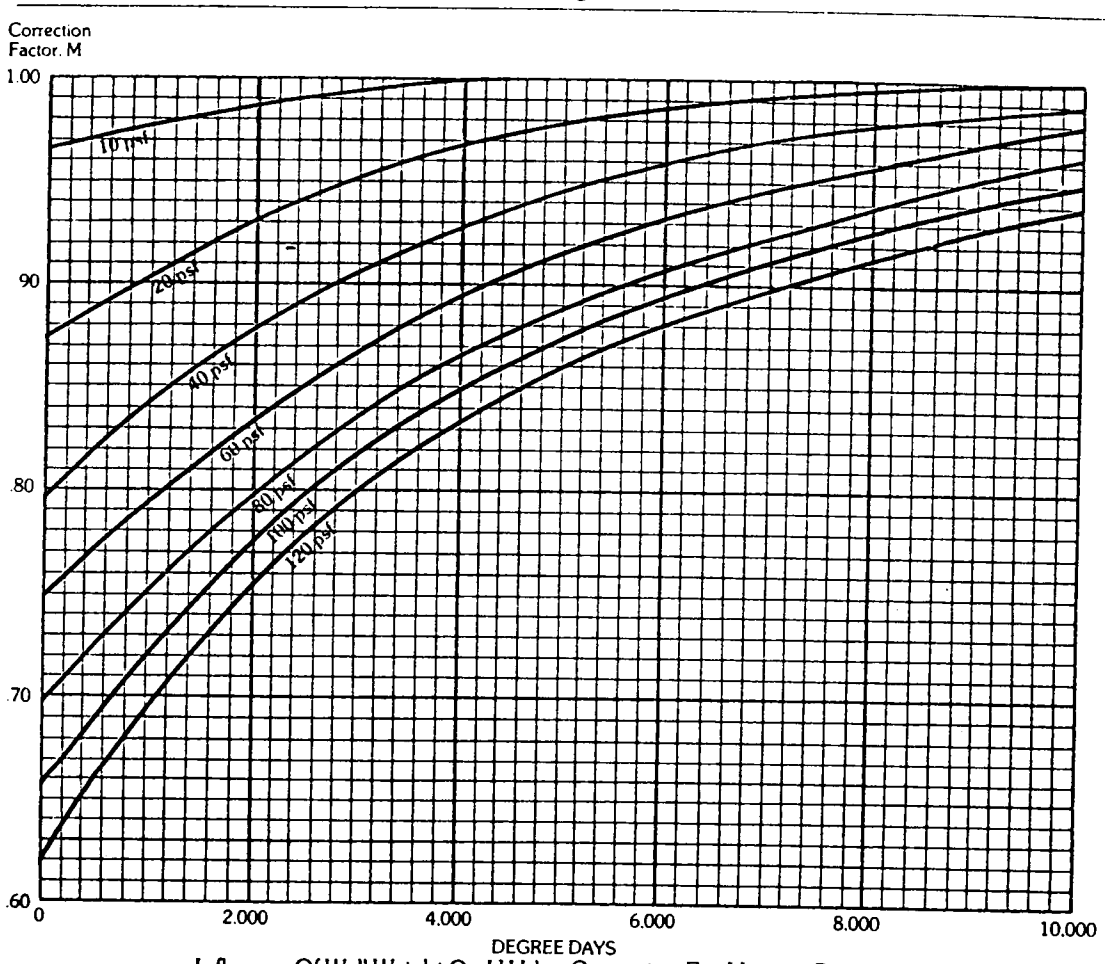
APPENDIX A

SAMPLES OF STATE CODES ON ENERGY CONSERVATION IN BUILDINGS

This appendix contains samples of the Utah, Florida and California building codes, in reference to space conditioning energy use.

Capacity Insulation Correction Graph

Figure 6-8



Influence Of Wall Weight On U Value Correction For Heating Design

EXCEPTION: WHEN MORE ACCURATE FACTORS ARE AVAILABLE FOR A SPECIFIC LOCALITY, THAT DATA MAY BE USED IN LIEU OF THIS CHART.

FLORIDA ENERGY EFFICIENCY CODE FOR BUILDING CONSTRUCTION

FORM 900-B-86

SECTION 9 — RESIDENTIAL POINT SYSTEM METHOD
DEPARTMENT OF COMMUNITY AFFAIRS

CLIMATE ZONES
CENTRAL 4 5 6

PROJECT NAME
AND ADDRESS:
BUILDER:
OWNER:

PERMITTING OFFICE
CIRCLE CLIMATE ZONE: 4 5 6
PERMIT NO.:
JURISDICTION NO.:

DETACHED: NEW ADD
ATTACHED: NEW ADD

CHECK IF WORST CASE CALCULATION
IF MULTIFAMILY, NUMBER OF UNITS

CONDITIONED FLOOR AREA	CEILING INSULATION: UNDER ATTIC	CEILING INSULATION: SGL. ASSEMBLY
	R =	R =

GLASS AREA AND TYPE: CLEAR		TINT.FILM.SOLAR SCREEN	
	SGL		SGL
	DBL		DBL

NET WALL AREA AND INSULATION

CBS	R=	FRAME	R=	STEEL STUD	R=	LOG	R=

DUCTS	COOLING SYSTEM	HEATING SYSTEM		HOT WATER SYSTEM	
IN UNCOND. SPACE R =	CENTRAL / NONE	ELECTRIC STRIP	HEAT PUMP	ELECTRIC	SOLAR
	ROOM	NATURAL GAS	ROOM/PTHP	NATURAL GAS	HEAT RECOVERY
IN COND SPACE R =	PTAC	OTHER FUELS	NONE	OTHER FUELS	DED. HEAT PUMP
	SEER/EER =	COP/AFUE =		EF =	SF/EF =
				NUMBER OF BEDROOMS =	

INFILTRATION PRACTICE USED: #1 #2 #3

TOTAL AS-BUILT POINTS ÷ TOTAL BASE POINTS x 100 = CALCULATED E.P.I

CALCULATED ENERGY PERFORMANCE INDEX MUST NOT EXCEED 100 POINTS.

In accordance with Section 553.907 F.S., I hereby certify that the plans and specifications covered by this calculation are in compliance with the Florida Energy Code.

OWNER/AGENT:

DATE:

Review of the plans and specifications covered by this calculation indicates compliance with the Florida Energy Code. Before construction is completed, this building will be inspected for compliance in accordance with Section 553.908 F.S.

BUILDING OFFICIAL:

DATE:

FLORIDA ENERGY EFFICIENCY CODE FOR BUILDING CONSTRUCTION

FORM 900-A-86

SECTION 9 — RESIDENTIAL POINT SYSTEM METHOD
DEPARTMENT OF COMMUNITY AFFAIRS

CLIMATE ZONES
CENTRAL 4 5 6

This form may be used to demonstrate compliance with the Energy Code for new single-family detached or multifamily attached dwellings under Section 9. An alternative to this method for single-family detached dwellings, and multifamily attached dwellings of three stories or less, is provided in Section 10. Multifamily attached dwellings greater than three stories must comply under Section 9 or 5. Additions to existing residential buildings must comply under Section 9 or 10. Additional information may be obtained from your local building department or the Department of Community Affairs, Energy Code Program, 2571 Executive Center Circle East, Tallahassee, Florida 32301-8244.

PROJECT NAME	PERMITTING OFFICE:
AND ADDRESS:	CIRCLE CLIMATE ZONE: 4 5 6
BUILDER:	PERMIT NO.:
OWNER:	JURISDICTION NO.:

DETACHED ☐ NEW ☐ ADD.	CHECK IF WORST CASE CALCULATION	☐ IF MULTIFAMILY, NUMBER OF UNITS		GLASS AREA AND TYPE			
				CLEAR		TINT,FILM,SOLAR SCREEN	
ATTACHED ☐ NEW ☐ ADD.	CONDITIONED FLOOR AREA	CEILING INSULATION UNDER ATTIC	CEILING INSULATION SGL. ASSEMBLY		SGL		SGL
		R =	R =		DBL		DBL

NET WALL AREA AND INSULATION							
CBS	R=	FRAME	R=	STEEL STUD	R=	LOG	R=

DUCTS	COOLING SYSTEM		HEATING SYSTEM		HOT WATER SYSTEM	
IN UNCOND. SPACE R =	☐ CENTRAL	☐ NONE	☐ ELECTRIC STRIP	☐ HEAT PUMP	☐ ELECTRIC	☐ SOLAR
	☐ ROOM		☐ NATURAL GAS	☐ ROOM/PTHP	☐ NATURAL GAS	☐ HEAT RECOVERY
IN COND SPACE R =	☐ PTAC		☐ OTHER FUELS	☐ NONE	☐ OTHER FUELS	☐ DED. HEAT PUMP
	SEER/EER =		COP/AFUE =		EF =	SF/EF =
					NUMBER OF BEDROOMS =	

INFILTRATION PRACTICE USED ☐ #1 ☐ #2 ☐ #3	TOTAL AS-BUILT POINTS	÷	TOTAL BASE POINTS	x 100 =	CALCULATED E.P.I
	CALCULATED ENERGY PERFORMANCE INDEX MUST NOT EXCEED 100 POINTS.				

In accordance with Section 553.907 F.S., I hereby certify that the plans and specifications covered by this calculation are in compliance with the Florida Energy Code.

OWNER/AGENT: _____

DATE: _____

Review of the plans and specifications covered by this calculation indicates compliance with the Florida Energy Code. Before construction is completed, this building will be inspected for compliance in accordance with Section 553.908 F.S.

BUILDING OFFICIAL: _____

DATE: _____

9A PRESCRIPTIVE MEASURES (Must be met or exceeded by all residences.)

COMPONENTS	SECTION	REQUIREMENTS	CHECK
WINDOWS	904.1	MAXIMUM OF 0.5 CFM PER LINEAR FOOT OF OPERABLE SASH CRACK.	
EXTERIOR & ADJACENT DOORS	904.1	MAXIMUM OF 0.5 CFM PER SQ. FT. OF DOOR AREA. INCLUDES SLIDING GLASS DOORS, SOLID CORE, WOOD PANEL, INSULATED, OR GLASS DOORS ONLY.	
EXT. JOINTS & CRACKS	904.1	TO BE CAULKED, GASKETED, WEATHERSTRIPPED OR OTHERWISE SEALED.	
WATER HEATERS	904.2	MUST BEAR LABEL INDICATING COMPLIANCE WITH ASHRAE STANDARD 90 OR COMPLY WITH EFFICIENCY AND STANDBY LOSS REQUIREMENTS. SWITCH OR CLEARLY MARKED CIRCUIT BREAKER (ELECTRIC), OR CUT-OFF (GAS) MUST BE PROVIDED. AN EXTERNAL OR BUILT-IN HEAT TRAP MUST BE PROVIDED.	
SWIMMING POOLS & SPAS	904.3	SPAS & HEATED POOLS MUST HAVE COVERS (EXCEPT SOLAR HEATED). NON-COMMERCIAL POOLS MUST HAVE A PUMP TIMER. GAS SPA & POOL HEATERS MUST HAVE MINIMUM THERMAL EFFICIENCY OF 75%.	
HOT WATER PIPES	904.4	INSULATION IS REQUIRED ONLY FOR RECIRCULATING SYSTEMS. IN SUCH CASES, PIPING HEAT LOSS SHALL BE LIMITED TO 17.5 BTU/H/LINEAR FOOT OF PIPE.	
SHOWER HEADS	904.5	WATER FLOW MUST BE RESTRICTED TO NO MORE THAN 3 GALLONS PER MINUTE AT 20 TO 80 PSIG.	
HVAC DUCT CONSTRUCTION	903.2 904.6	CONSTRUCTED IN ACCORDANCE WITH INDUSTRY STANDARDS & LOCAL MECHANICAL CODES. DUCTS IN UNCONDITIONED SPACE MUST BE INSULATED TO MINIMUM R- 4.2 & JOINTS MUST BE SEALED.	
HVAC CONTROLS	904.7	SEPARATE READILY ACCESSIBLE MANUAL OR AUTOMATIC THERMOSTAT FOR EACH SYSTEM.	
CEILING INSUL	904.9	MINIMUM R-19.	

9. HEATING SYSTEM MULTIPLIERS (HSM) — CLIMATE ZONES 4 5 6

SYSTEM TYPE		HEATING SYSTEM MULTIPLIERS						
Heat Pump	COP	2.5 - 2.69	2.7 - 2.89	2.9 - 3.09	3.1 - 3.29	3.3 - 3.49	3.5 - 3.69	3.7 - Up
	HSM	.54	.50	.47	.44	.41	.39	.37
Electric Strip	HSM	1.0						
Gas & Other Fuels	HSM	1.0 (See Table 9J for Credit Multipliers)						
PTHP & Room Units	HSM	HSM for COP 2.2 - 2.49 = .63. See above for COP >2.49.						
Minimums: Central Units 2.5 COP. PTHP & Room Units 2.2 COP. COP means Coefficient of Performance								

9J HEATING CREDIT MULTIPLIERS (HCM)

SYSTEM TYPE		HEATING SYSTEM MULTIPLIERS						
Multizone	HCM	.90						
Natural Gas	AFUE	.60 - .64	.65 - .69	.70 - .74	.75 - .79	.80 - .84	.85 - .89	.90 - Up
	HCM	.44	.41	.38	.35	.33	.31	.30
Other Fuels	HCM	.69	.63	.59	.55	.51	.48	.46
Where more than one credit is claimed, multiply HCM's together. Enter product on page 4. AFUE means Annual Fuel Utilization Efficiency.								

9K COOLING SYSTEM MULTIPLIERS (CSM)

SYSTEM TYPE		COOLING SYSTEM MULTIPLIERS									
Central Units	SEER	7.8-7.9	8.0-8.4	8.5-8.9	9.0-9.4	9.5-9.9	10.0-10.4	10.5-10.9	11.0-11.4	11.5-11.9	12.0-& Up
	CSM	.44	.43	.40	.38	.36	.34	.32	.31	.30	.28
PTAC & Room Unit	CSM	CSM for EER 7.5 - 7.7 = .46. For EER's >7.7 use multipliers above.									
Minimums: Central Units 7.8 SEER. Room Units 7.5 EER. PTAC under 13,000 BTU/H 7.5 EER, and over 13,000 BTU/H 7.0 EER. SEER means Seasonal Energy Efficiency Ratio. EER means Energy Efficiency Ratio.											

9L COOLING CREDIT MULTIPLIERS (CCM)

SYSTEM TYPE		COOLING CREDIT MULTIPLIERS
Ceiling Fans	CCM	.86
Multizone	CCM	.90
Cross Ventilation or Whole House Fan (Credit for only one)	CCM	.95
Where more than one credit is claimed, multiply CCM's together. Enter product on page 2.		

9M HOT WATER MULTIPLIERS (HWM)

SYSTEM TYPE		HOT WATER MULTIPLIERS							
Electric Resistance	EF	.80 - .81	.82 - .83	.84 - .85	.86 - .87	.88 - .90	.91 - .93	.94 - .96	.97 & UP
	HWM	3879	3785	3695	3609	3527	3411	3302	3200
Natural Gas	EF	.48 - .49	.50 - .51	.52 - .53	.54 - .55	.56 - .57	.58 - .59	.60 - .61	.62 & Up
	HWM	1722	1653	1589	1530	1476	1425	1377	1333
Other Fuels	HWM	2662	2556	2458	2367	2282	2203	2130	2061
Water heaters must comply with prescriptive means of Table 9A. EF means Energy Factor.									

9N HOT WATER CREDIT MULTIPLIERS (HWCM)

SYSTEM TYPE		HOT WATER CREDIT MULTIPLIERS									
Solar Water Heater	SF	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
	HWCM	.9	.8	.7	.6	.5	.4	.3	.2	.1	.0
Heat Recovery Unit	With	Air-conditioner					Heat Pump				
	HWCM	.62					.58				
Dedicated Heat Pump	EF	2.0-2.49		2.5-2.99			3.0-3.49		3.5 & Up		
	HWCM	.44		.35			.29		.25		
A HWM must be used in conjunction with all HWCM. See Table 9M. SF means Solar Fraction. EF means Energy Factor.											

9P INFILTRATION REDUCTION PRACTICE COMPLIANCE CHECKLIST (See Section 903.2(f))

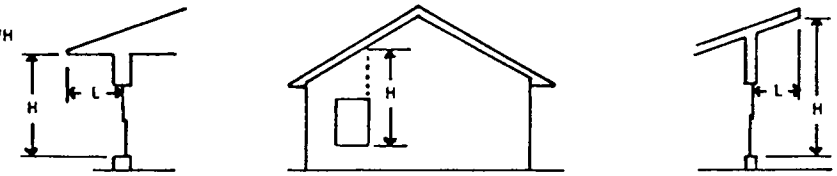
COMPONENTS	REQUIREMENTS FOR EACH PRACTICE	CHECK
PRACTICE #1	COMPLY WITH ALL INFILTRATION PRESCRIPTIVES ON TABLE 9A.	
PRACTICE #2	COMPLY WITH PRACTICE #1 AND THE FOLLOWING:	
Exterior Walls and Floors	Top plate penetrations sealed. Infiltration barrier installed. Sole plate/floor joint caulked or sealed.	
Exterior Walls & Ceilings	Penetrations, joints and cracks on interior surface caulked, sealed and gasketed.	
Ductwork	Ductwork in unconditioned space must be sealed.	
Fireplaces	Equipped with outside combustion air, doors, and flue dampers.	
Exhaust Fans	Equipped with dampers. Combustion devices see 903.2(f).	
PRACTICE #3	COMPLY WITH PRACTICES #1 AND #2 AND THE FOLLOWING:	
Ceilings	Infiltration barrier installed.	
Interior Walls	Top plate penetrations sealed or joints & cracks on interior walls caulked, sealed or gasketed.	
Recessed Lights	Sealed from conditioned space & insulated from ventilated attic spaces.	
Ductwork	All ductwork located in conditioned space.	
Combustion Appliances	Be in unconditioned space (except direct vent), draw air from unconditioned space, exhaust by-products to outside. Stoves see 903.2(f).	

WINTER POINT MULTIPLIERS

9B WINTER OVERHANG FACTORS (WOF) CLIMATE ZONES 4 5 6

ORIEN-TATION	OVERHANG RATIO 0.0 - 0.17	0.18-0.26	0.27-0.35	0.36-0.46	0.47-0.57	0.58-0.70	0.71-0.83	0.84-1.18	1.19-1.72	1.73-2.73	2.74-5.66	5.67-Up
	SINGLE PANE GLASS											
N	1.0	1.05	1.06	1.10	1.13	1.15	1.18	1.20	1.24	1.29	1.34	1.38
NE/NW	1.0	1.10	1.15	1.20	1.25	1.30	1.35	1.39	1.50	1.59	1.67	1.74
E/W	1.0	.57	.19	-.20	-.65	-1.05	-1.48	-2.03	-3.01	-4.06	-5.04	-5.71
SE/SW	1.0	.90	.80	.68	.54	.39	.22	.05	-.33	-.71	-1.01	-1.20
S	1.0	.92	.83	.70	.54	.36	.13	-.13	-.70	-.98	-1.09	-1.16
	DOUBLE PANE GLASS											
N	1.0	1.07	1.11	1.14	1.18	1.21	1.24	1.28	1.34	1.40	1.47	1.53
NE/NW	1.0	1.16	1.24	1.32	1.41	1.48	1.56	1.63	1.80	1.94	2.08	2.18
E/W	1.0	.82	.66	.50	.31	.15	-.03	-.26	-.66	-1.10	-1.50	-1.78
SE/SW	1.0	.92	.85	.76	.65	.54	.41	.28	-.01	-.30	-.52	-.67
S	1.0	.94	.87	.78	.65	.51	.33	.13	-.30	-.51	-.60	-.65

OVERHANG RATIO = L/H



9C WALL WINTER POINT MULTIPLIERS (WPM)

FRAME			CONCRETE BLOCK						FACE BRICK		LOG	
				INTERIOR INSUL.			EXT. INSUL.		R-VALUE	WOOD FR		
WOOD				NORM WT.		LT WT	NORM	LT WT	0 - 6.9	7.0	6 INCH	
R-VALUE	EXT	ADJ	R-VALUE	EXT	ADJ	EXT	EXT	EXT	7 - 10.9	2.1	R-VALUE	EXT
0 - 6.9	6.8	5.3	0 - 2.9	6.0	3.1	4.7	6.0	4.7	11 - 18.9	1.7	0 - 2.9	2.2
7 - 10.9	2.5	2.1	3 - 4.9	3.8	2.3	3.1	2.8	2.3	19 - 25.9	1.0	3 - 6.9	1.2
11 - 12.9	2.0	1.8	5 - 6.9	2.9	1.9	2.4	2.0	1.7	26 & Up	.6	7 & Up	.9
13 - 18.9	1.8	1.6	7 - 10.9	2.3	1.5	1.9	1.5	1.2	R-VALUE	BLOCK	8 INCH	
19 - 25.9	1.1	1.0	11 - 18.9	1.5	1.1	1.3	.8	.8	0 - 2.9	3.7	R-VALUE	EXT
26 & Up	.7	.7	19 - 25.9	.8	.7	.8			3 - 6.9	2.6	0 - 2.9	1.2
STEEL			26 & Up	.5	.5	.5			7 - 9.9	1.8	3 - 6.9	.9
R-VALUE	EXT	ADJ							10 & Up	1.3	7 & Up	.7
0 - 6.9	9.4	6.7										
7 - 10.9	4.4	3.3										
11 - 12.9	3.3	2.6										
13 - 18.9	3.0	2.4										
19 - 25.9	2.6	2.2										
26 & Up	1.4	1.2										

9E CEILING WINTER POINT MULTIPLIERS (WPM)

UNDER ATTIC		SINGLE ASSEMBLY		CONCRETE DECK ROOF		
					CEILING TYPE	
R-VALUE	WPM	R-VALUE	WPM	R-VALUE	DROPPED	EXPOSED
19 - 21.9	1.0	5 - 6.9	4.1	10 - 13.9	1.2	1.3
22 - 25.9	.9	7 - 8.9	2.6	14 - 20.9	.7	.7
26 - 29.9	.7	9 - 10.9	2.0	21 & Up	.4	.3
30 - 37.9	.6	11 - 12.9	1.6			
38 & Up	.4	13 - 18.9	1.5			
		19 - 25.9	1.1			
		26 & Up	.6			
CREDIT MULTIPLIER FOR ATTIC RADIANT BARRIER = .63						

9D DOOR WINTER POINT MULTIPLIERS (WPM)

DOOR TYPE	EXT	ADJ
WOOD	9.5	6.9
INSULATED	10.5	7.6

9F FLOOR WINTER POINT MULTIPLIERS (WPM)

SLAB-ON-GRADE EDGE INSULATION		RAISED CONCRETE		RAISED WOOD (See 903.2(e))	
R-VALUE	WPM	R-VALUE	WPM	R-VALUE	WPM
0 - 2.9	2.5	0 - 2.9	4.0	0 - 6.9	3.5
3 - 4.9	-1.7	3 - 4.9	1.8	7 - 10.9	1.1
5 - 6.9	-2.4	5 - 6.9	1.1	11 - 18.9	.8
7 & Up	-2.7	7 & Up	.8	19 & Up	.4

9G INFILTRATION WINTER POINT MULTIPLIERS

INFILTRATION PRACTICE (See Table 9P)	WPM
PRACTICE # 1	6.2
PRACTICE # 2	4.1
PRACTICE # 3	2.2

9H DUCT MULTIPLIERS (DM)

R-VALUE	With Return Air Duct	W/O Return Air Duct
4.2 - 4.9	1.14	1.10
5.0 - 6.6	1.12	1.08
6.7 & Up	1.09	1.06
DUCTS IN CONDITIONED SPACE	1.00	1.00

GLASS

OR	GLASS AREA	x	BASE WPM	=	BASE WINTER POINTS
N			5.6		
NE			3.5		
E			- 5.6		
SE			-13.4		
S			-14.0		
SW			-13.4		
W			- 5.6		
NW			3.5		
H*			-14.0		

OR	GLASS AREA	x	SINGLE WPM CLEAR	SINGLE WPM TINT**	OR	DOUBLE WPM CLEAR	DOUBLE WPM TINT**	x	WOF (9B)	=	AS-BUILT GLASS WIN. PTS.
N			9.6	9.6		5.6	6.1				
NE			7.4	7.3		3.5	4.2				
E			- 2.2	- 2.0		- 5.6	- 3.6				
SE			-10.3	- 9.7		-13.4	-10.4				
S			-10.9	-10.2		-14.0	-11.0				
SW			-10.3	- 9.7		-13.4	-10.4				
W			- 2.2	- 2.0		- 5.6	- 3.6				
NW			7.4	7.3		3.5	4.2				
H*			-32.1	-28.0		-27.0	-21.5				

.15	x	COND. FLOOR AREA	+	TOTAL GLASS AREA	=	BASE ADJ. FACTOR	x	BASE GLASS SUBTOTAL	=	ADJUSTED GLASS BASE WP
.15										

AS-BUILT GLASS SUBTOTAL

	COMPONENT DESCRIPTION	AREA	x	BASE WIN. PT. MULT.	=	BASE WINTER POINTS
WALL	EXTERIOR			1.1		
	ADJACENT			1.8		
DOORS	EXTERIOR			10.5		
	ADJACENT			7.6		
CEIL	UNDER ATTIC OR SINGLE ASSEMBLY			.6		
				.6		
				.6		
FLOOR	SLAB			- 1.9		
	RAISED			- .2		
	FOR SLAB ON GRADE USE PERIMETER LENGTH ALONG CONDITIONED FLOOR IN PLACE OF AREA					
INFILTRATION				4.1		
	USE FLOOR AREA OF CONDITIONED SPACE.					

COMPONENT DESCRIPTION	AREA	x	WIN. PT. MULT. (9C THRU 9G)	=	AS-BUILT WINTER POINTS

TOTAL COMPONENT BASE WINTER POINTS	

TOTAL COMPONENT AS-BUILT WINTER POINTS	

HEATING SYSTEM	BASE HSM	x	TOTAL BASE WIN. PTS.	=	BASE HEATING POINTS
	1.14				

TOTAL AS-BUILT WIN. PTS.	x	AS-BUILT DM (9H)	x	AS-BUILT HSM (9I)	x	AS-BUILT HCM (9J)	=	AS-BUILT HEATING POINTS

TOTAL	BASE COOLING POINTS (From P.2)	+	BASE HEATING POINTS	+	BASE HOT WATER POINTS (From P.2)	=	TOTAL BASE POINTS (Enter on P.1)

TOTAL	AS-BUILT COOLING POINTS (From P.2)	+	AS-BUILT HEATING POINTS	+	AS-BUILT HOT WATER POINTS (From P.2)	=	TOTAL AS-BUILT POINTS (Enter on P.1)

* H = Horizontal Glass (Skylights)

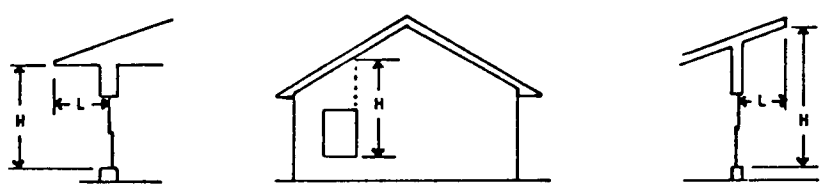
** For Shading Coefficient less than 0.83., see sec. 903.2(a). Tint Multipliers may be used for glass with solar screens, film, or tint.

SUMMER POINT MULTIPLIERS

9B SUMMER OVERHANG FACTORS (SOF) For single and double pane glass. CLIMATE ZONES 4 5 6

ORIEN-TATION	OVERHANG RATIO											
	0.0 - 0.17	0.18 - 0.26	0.27 - 0.35	0.36 - 0.46	0.47 - 0.57	0.58 - 0.70	0.71 - 0.83	0.84 - 1.18	1.19 - 1.72	1.73 - 2.73	2.74 - 5.66	5.67 - Up
N	1.0	.91	.87	.83	.79	.75	.72	.69	.62	.56	.50	.44
NE/NW	1.0	.91	.85	.79	.72	.68	.63	.58	.50	.40	.36	.30
E/W	1.0	.92	.85	.78	.70	.64	.58	.52	.42	.33	.26	.20
SE/SW	1.0	.90	.81	.72	.62	.55	.49	.42	.33	.27	.22	.19
S	1.0	.87	.77	.67	.57	.50	.45	.39	.32	.28	.25	.22

OVERHANG RATIO = L/H



9C WALL SUMMER POINT MULTIPLIERS (SPM)

FRAME		
WOOD		
R-VALUE	EXT	ADJ
0 - 6.9	6.4	2.2
7 - 10.9	2.3	.8
11 - 12.9	1.9	.7
13 - 18.9	1.7	.6
19 - 25.9	1.0	.3
26 & Up	.6	.2
STEEL		
R-VALUE	EXT	ADJ
0 - 6.9	8.9	2.9
7 - 10.9	4.1	1.3
11 - 12.9	3.0	1.0
13 - 18.9	2.8	0.9
19 - 25.9	2.4	0.8
26 & Up	1.3	0.4

CONCRETE BLOCK					
	INTERIOR INSUL.			EXT. INSUL.	
	NORM WT.		LT WT	NORM	LT WT
R-VALUE	EXT	ADJ	EXT	EXT	EXT
0 - 2.9	2.5	.9	1.8	2.5	1.8
3 - 4.9	1.4	.7	1.1	.7	.8
5 - 6.9	1.0	.6	.8	.3	.3
7 - 10.9	.8	.4	.6	.1	.1
11 - 18.9	.4	.3	.3	.0	.0
19 - 25.9	.2	.2	.1		
26 & Up	.1	.1	.0		

FACE BRICK	
R-VALUE	WOOD FR
0 - 6.9	2.9
7 - 10.9	.6
11 - 18.9	.4
19 - 25.9	.2
26 & Up	.1
R-VALUE	BLOCK
0 - 2.9	1.0
3 - 6.9	.6
7 - 9.9	.4
10 & Up	.2

LOG	
6 INCH	
R-VALUE	EXT
0 - 2.9	1.7
3 - 6.9	1.1
7 & Up	.6
8 INCH	
R-VALUE	EXT
0 - 2.9	1.0
3 - 6.9	.8
7 & Up	.7

9D DOOR SUMMER POINT MULTIPLIERS (SPM)

DOOR TYPE	EXT	ADJ
WOOD	9.1	2.9
INSULATED	9.9	3.2

9E CEILING SUMMER POINT MULTIPLIERS (SPM)

UNDER ATTIC		SINGLE ASSEMBLY		CONCRETE DECK ROOF		
					CEILING TYPE	
R-VALUE	SPM	R-VALUE	SPM	R-VALUE	DROPPED	EXPOSED
19 - 21.9	1.1	5 - 6.9	6.3	10 - 13.9	3.0	3.3
22 - 25.9	.9	7 - 8.9	4.2	14 - 20.9	2.0	2.1
26 - 29.9	.7	9 - 10.9	3.3	21 & Up	1.4	1.3
30 - 37.9	.6	11 - 12.9	2.7			
38 & Up	.4	13 - 18.9	2.4			
		19 - 25.9	1.8			
		26 & Up	1.1			

CREDIT MULTIPLIER FOR ATTIC RADIANT BARRIER = .53

9F FLOOR SUMMER POINT MULTIPLIERS (SPM)

SLAB-ON-GRADE EDGE INSULATION		RAISED CONCRETE		RAISED WOOD (See 903.2(e))	
R-VALUE	SPM	R-VALUE	SPM	R-VALUE	SPM
0 - 2.9	-31.9	0 - 2.9	-1.0	0 - 6.9	- .7
3 - 4.9	-31.8	3 - 4.9	-1.7	7 - 10.9	- .8
5 - 6.9	-31.7	5 - 6.9	-1.7	11 - 18.9	- .8
7 & Up	-31.6	7 & Up	-1.7	19 & Up	- .7

9G INFILTRATION SUMMER POINT MULTIPLIERS

INFILTRATION PRACTICE (See Table 9P)	SPM
PRACTICE # 1	13.8
PRACTICE # 2	10.9
PRACTICE # 3	7.6

9H DUCT MULTIPLIERS (DM)

R-VALUE	With Return Air Duct	W/O Return Air Duct
4.2 - 4.9	1.14	1.10
5.0 - 6.6	1.12	1.08
6.7 & Up	1.09	1.06
DUCTS IN CONDITIONED SPACE	1.00	1.00

SUMMER CALCULATIONS

CLIMATE ZONES 4 5 6

GLASS

OR	GLASS AREA	x	BASE SPM	=	BASE SUMMER POINTS
N			47.8		
NE			71.7		
E			102.0		
SE			104.1		
S			90.9		
SW			104.1		
W			102.0		
NW			71.7		
H*			90.9		

OR	GLASS AREA	x	SINGLE SPM CLEAR	SINGLE SPM TINT**	OR	DOUBLE SPM CLEAR	DOUBLE SPM TINT**	x	SOF (9B)	=	AS-BUILT GLASS SUM. PTS.
N			51.0	51.5		47.8	43.5				
NE			77.2	76.6		71.7	63.4				
E			109.2	107.1		102.0	87.3				
SE			112.9	110.3		104.1	89.4				
S			100.2	98.3		90.9	78.8				
SW			112.9	110.3		104.1	89.4				
W			109.2	107.1		102.0	87.3				
NW			77.2	76.6		71.7	63.4				
H*			367.7	303.3		324.6	238.1				

.15	x	COND. FLOOR AREA	÷	TOTAL GLASS AREA	=	BASE ADJ. FACTOR	x	BASE GLASS SUBTOTAL	=	ADJUSTED GLASS BASE SP
.15										

AS-BUILT GLASS SUBTOTAL

	COMPONENT DESCRIPTION	AREA	x	BASE SUM. PT. MULT.	=	BASE SUMMER POINTS
WALL	EXTERIOR			1.0		
	ADJACENT			.7		
DOORS	EXTERIOR			9.9		
	ADJACENT			3.2		
CEIL	UNDER ATTIC			.6		
	OR SINGLE			.6		
	ASSEMBLY			.6		
FLOOR	SLAB			– 31.8		
	RAISED			– 3.43		
	FOR SLAB-ON-GRADE USE PERIMETER LENGTH ALONG CONDITIONED FLOOR IN PLACE OF AREA.					
INFILTRATION				10.9		
	USE FLOOR AREA OF CONDITIONED SPACE.					

COMPONENT DESCRIPTION	AREA	x	SUM. PT. MULT. (9C THRU 9G)	=	AS-BUILT SUMMER POINTS

TOTAL COMPONENT BASE SUMMER POINTS

TOTAL COMPONENT AS-BUILT SUMMER POINTS

COOLING SYSTEM	BASE CSM	x	TOTAL BASE SUM. PTS.	=	BASE COOLING POINTS
	.43				

TOTAL AS-BUILT SUM. PTS.	x	AS-BUILT DM (9H)	x	AS-BUILT CSM (9K)	x	AS-BUILT CCM (9L)	=	AS-BUILT COOLING POINTS

HOT WATER SYSTEM	NUMBER OF BEDROOMS	x	BASE HWM	=	BASE HOT WATER POINTS
			3527		

AS-BUILT HOT WATER SYSTEM DESC.	NUMBER OF BEDROOMS	x	AS-BUILT HWM (9M)	x	AS-BUILT HWCM (9N)	=	AS-BUILT HOT WATER POINTS

* H = Horizontal Glass (Skylights)

** For Shading Coefficient less than 0.83, see sec. 903.2(a). Tint Multipliers may be used for glass with solar screens, film, or tint.

SAMPLE CALIFORNIA MASS CALCULATION PROCEDURE

Table 3-1. Minimum Thermal Mass Requirements

Building Type	Surface Area Ratio[1]	Minimum Heat Capacity[2]
Single Family Dwellings and Lodging Houses	7.8	36.5
Multi-family Buildings with Common Walls but with no Common Floor/Ceilings	5.0	23.1
All Other Multi-Family Buildings	4.0	18.4

1. Surface Area Ratio = $\frac{A_{mass}}{A_{glazing}}$.

2. Minimum Heat Capacity = $\frac{A_{mass} \times D \times C \times t}{A_{glazing}}$.

Where A_{mass} = the surface area of exposed mass, ft^2;

D = the density of the mass, lb/ft^3;

C = the specific heat of the mass, Btu/lb-°F;

t = the thickness of the mass, ft, up to a maximum thickness of 1/6 foot (2 inches);

$A_{glazing}$ = the surface area of the south-facing glazing, ft^2; and

A_{mass} and $A_{glazing}$ = total square foot of each type.

The density and specific heat of numerous mass materials are listed in Table 1 of Appendix A.

Alternatively, you may use the following procedure and Table 17 from Appendix A, Thermal Mass Factors, to calculate mass requirements for a given amount of glazing. The thermal mass factor incorporates the density, specific heat, and thickness of various mass types. This procedure enables you to calculate the south glazing area needed for a specific mass type or, conversely, the surface area of a particular type and thickness of mass needed to justify a desired level of south glazing. It is expressed as:

$$\frac{\text{Minimum Thermal Mass Surface Area}}{\text{Thermal Mass Factor}} = \text{Allowable South Glazing Area}$$

Thermal Mass Factor Procedure--The following procedure can be applied to Page 2 of the Calculation Work Sheet.

Step 1. Calculate the proposed glazing area for each orientation.

Step 2. Calculate the minimum allowable south glazing area required for the proposed conditioned floor area, in square feet. This minimum value is 6.4 percent of the floor area. (Nonsouth glazing must not exceed 9.6 percent.)

Step 3. Determine the surface area and thickness of each mass type. Only up to 2 inches of any mass material can be counted as thermal mass. In a wood or metal frame assembly with multiple layers of gypsum board or tile over gypsum board, subtract 1/2 inch of gypsum for each wall and ceiling surface.

For example, a partition wall composed of 4 inch adobe block would count as 2 inches of mass on each exposed surface, excluding the ends. A 4 inch concrete slab-on-ground floor would count as 2 inches of mass except for that portion of slab covered by carpets walls or cabinets, or enclosed in closets.

If a mass wall is exposed on both sides, count both sides as surface area, but do not count mass thicknesses deeper than the wall center line or greater than 2 inches. The idea is to not "double count" mass.

Step 4. Refer to the appropriate building type in Table 17 of Appendix A to locate the mass factor for the specified mass type and thickness.

Step 5. For each mass type, divide the mass surface area by the mass "factor" to determine the allowable south glazing area associated with the specific mass type.

$$\frac{\text{Thermal Mass Surface Area}}{\text{Thermal Mass Factor}} = \text{Allowable South Glazing Area}$$

Step 6. Repeat steps 4 and 5 for each mass material and thickness.

Step 7. Total the allowable south glazing areas for all thermal mass materials used. If this amount is less than the proposed south glazing area, thermal mass must be added or the proposed south glazing area must be reduced. However, the south glazing area must be equal to or greater than 6.4 percent of the floor area.

ıble 12. Thermal Mass Factors (required mass area for 1 ft^2 of glass, by material and thickness) Page 1 of 3

SINGLE FAMILY DWELLINGS AND LODGING HOUSES

Thermal Mass Material		Thermal Mass Thickness (Inches)						
	1/4	1/2	3/4	1	1-1/4	1-1/2	1-3/4	2
Adobe	68.8	34.4	22.9	17.2	13.7	11.4	9.8	8.6
Clay	126.4	63.2	42.1	31.6	25.2	21.0	18.0	15.8
Brick: Common	73.0	36.5	24.3	18.2	14.6	12.1	10.4	9.1
Face	67.3	33.6	22.4	16.8	13.4	11.2	9.6	8.4
Concrete: Block	75.8	37.9	25.2	18.9	15.1	12.6	10.8	9.1
Lightweight Aggr.	99.5	49.7	33.1	24.8	19.9	16.5	14.2	12.4
Normal Aggr.	59.5	29.7	19.8	14.8	11.9	9.9	8.5	7.4
Water	28.0	14.0	9.3	7.0	5.6	4.6	4.0	3.5
Earth	31.1	15.5	10.3	7.7	6.2	5.1	4.4	3.8
Stone: Lime	92.2	46.1	30.7	23.0	18.4	15.3	13.1	11.5
Granite	55.0	27.5	18.3	13.7	11.0	9.1	7.8	6.8
Plaster	83.4	41.7	27.8	20.8	16.6	13.9	11.9	10.4
Gypsum	134.7	67.3	44.9	33.6	25.9	22.4	19.2	16.8
Phase Change	39.8	19.9	13.2	9.9	7.9	6.6	5.6	4.9
Tile	76.8	38.4	25.6	19.2	15.3	12.8	10.9	9.6
Wood: Hardwood	82.1	41.0	27.3	20.5	16.4	13.6	11.7	10.2
Softwood	105.0	52.5	35.0	26.2	21.0	17.5	15.0	13.1

Table 12. Thermal Mass Factors (required mass area for 1 ft^2 of glass, by material and thickness), Page 2 of 3

MULTI-FAMILY BUILDINGS WITH COMMON WALLS BUT NO COMMON FLOORS/CEILINGS

Thermal Mass Material	Thermal Mass Thickness (Inches)							
	1/4	1/2	3/4	1	1-1/4	1-1/2	1-3/4	2
Adobe	43.5	21.7	14.5	10.8	8.7	7.2	6.2	5.4
Clay	80.0	40.1	26.6	20.0	16.0	13.3	11.4	10.0
Brick: Common	46.2	23.1	15.4	11.5	9.2	7.7	6.6	5.7
Face	42.6	21.3	14.2	10.6	8.5	7.1	6.0	5.3
Concrete: Block	48	24	16	12	9.5	8	6.8	6
Lightweight Aggr.	63	31.5	21	15.7	12.5	10.5	9.0	7.8
Normal Aggr.	37.7	18.8	12.5	9.4	7.5	6.2	5.3	4.7
Water	17.7	8.8	5.9	4.4	3.5	2.9	2.5	2.2
Earth	19.6	9.8	6.5	4.9	3.9	3.2	2.8	2.4
Stone: Lime	58.3	29.1	19.4	14.5	11.6	9.7	8.3	7.2
Granite	34.8	17.4	11.6	8.7	6.9	5.8	4.9	4.3
Plaster	52.8	25.4	17.6	13.2	10.5	8.8	7.5	6.5
Gypsum	85.2	42.6	28.4	21.3	17.0	14.2	12.1	10.6
Phase Change	25.2	12.6	8.4	6.3	5.0	4.2	3.6	3.1
Tile	48.6	24.3	16.2	12.1	9.7	8.1	6.9	6.0
Wood: Hardwood	129.7	64.8	43.2	32.4	25.9	21.6	18.5	16.2
Softwood	165.9	82.9	55.3	41.4	33.1	27.6	23.7	20.7

Table 12. Thermal Mass Factors (required mass area for 1 ft^2 of glass, by material and thickness), Page 3 of 3

ALL OTHER MULTI-FAMILY BUILDINGS

Thermal Mass Material	Thermal Mass Thickness (Inches)							
	1/4	1/2	3/4	1	1-1/4	1-1/2	1-3/4	2
Adobe	34.7	17.3	11.5	8.6	8.7	5.7	4.9	4.3
Clay	63.7	31.8	21.2	15.9	12.7	10.6	9.1	7.9
Brick: Common	36.8	18.4	12.2	9.2	7.3	6.1	5.2	4.6
Face	33.9	16.9	11.3	8.4	6.7	5.6	4.8	4.2
Concrete: Block	38.2	19.1	12.7	9.5	7.6	6.3	5.4	4.7
Lightweight Aggr.	50.2	25	16.7	12.5	10	8.3	7.1	6.2
Normal Aggr.	36.	15	10	7.5	6	5	4.2	3.7
Water	14.1	7	4.7	3.5	2.8	2.3	2	1.7
Earth	15.6	7.8	5.2	3.9	3.1	2.6	2.2	1.9
Stone: Lime	46.4	23.2	15.4	11.6	9.2	7.7	6.6	5.8
Granite	27.7	13.8	9.2	6.9	5.5	4.6	3.9	3.4
Plaster	42.	21	14	10.5	8.4	7	6	5.2
Gypsum	67.9	33.9	22.6	16.9	13.5	11.3	9.7	8.4
Phase Change	20.	10	6.6	5	4	3.3	2.8	2.5
Tile	38.7	19.3	12.9	9.6	7.7	6.4	5.5	4.8
Wood: Hardwood	65.4	32.7	21.8	16.3	13.0	10.9	9.3	8.1
Softwood	83.6	41.8	27.8	20.9	16.7	13.9	11.9	10.4

APPENDIX B

FORMATTED THERMAL CONDUCTIVITY DATA

The information synthesized in Chapter 3, Thermal Properties of Masonry Block Products, represents current state-of-knowledge on the thermal properties of masonry block products. Based on the gaps identified in this body of knowledge, new directions for future research and testing are suggested in Chapter 4, thereby accomplishing one of the goals of this project. However, the problems identified with the majority of U.S. Codes and Standards (Chapter 2) are of such magnitude that it may not be advisable to wait until new research and testing is completed in order to address them. Many of these problems can be resolved today, using the information already contained in this study. Such revisions would represent a major improvement in the adequacy of U.S. building regulations and a step forward with regard to accepted calculation techniques. To that end this chapter organizes the data presented in Chapter 3 so that it can be of direct use to the codes and Standards community, and particularly to ASHRAE.

The data base includes over 700 data points*, expressed in both inch-lb and SI units, with references to author, date and, when available, test method and specimen size. The papers themselves are listed in the bibliography of Chapter 6.

Because this type of data presentation facilitates verification of results, it is hoped that it will be considered by standard and code-writing bodies. Also, given the amount of information structured in the data base, other researchers may be able to use it for purposes beyond those addressed in this report.

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* It should be noted that for some USSR and Polish data the test method is not given. It is probable that the hot-plate method, conforming to GOST 7076-54 was used; test equipment manufactured by Karl Weiss Co. or "Fentron" of East Germany was widely used in the USSR from 1960 to 1975.

MASONRY COMPONENTS CONDUCTIVITY DATA

AUTHORS(S)	DATE	INCH-LB DENSITY (lb/ft3)	INCH-LB CONDUCTIVITY (Btu. in/h ft2 F)	SI-UNITS DENSITY (kg/m3)	SI-UNITS CONDUCTIVITY (W/m k)	TEST METHOD	SPECIMEN	REMARKS
I. Hardened Neat Cement Pastes		Concretes						
Harmathy, T. Z.	1970	90.0	3.42	1,441.7	0.493	Transient		
		111.0	4.43	1,778.0	0.639			
		127.0	4.88	2,034.3	0.704			
Spooner, D.C.	1977	64.0	1.80	1,025.2	0.260	Hot plate		
		70.2	2.08	1,124.5	0.300			
		72.4	2.26	1,159.7	0.326			
		84.2	2.64	1,348.8	0.381			
		92.4	3.05	1,480.1	0.440			
		108.0	3.75	1,730.0	0.541			
Spivak, N.Y.	1979	121.7	3.97	1,949.4	0.573			
		120.4	4.83	1,928.6	0.697			
		124.8	4.20	1,999.1	0.606			
Valore, R.C.	1954	16.0	0.600	256.3	0.087	Summary; mainly		
		20.0	0.650	320.4	0.094	guarded hot-plate		
		23.5	0.550	376.4	0.094			
		30.0	0.750	480.6	0.108			
		31.0	1.000	496.6	0.144			
		30.1	0.900	482.2	0.130			
		38.2	1.100	611.9	0.159			
		41.5	1.100	664.8	0.159			
		42.5	1.250	680.8	0.180			
		43.5	1.200	696.8	0.173			
		47.3	1.260	757.7	0.182			
		49.7	1.360	796.1	0.196			
		50.3	1.050	805.7	0.151			
		52.9	1.470	874.4	0.212			
		59.7	1.800	956.3	0.260			
		59.8	1.900	957.9	0.274			

AUTHORS(S)	DATE	INCH-LB		SI-UNITS		TEST METHOD	SPECIMEN	REMARKS
		DENSITY (lb/ft3)	CONDUCTIVITY (Btu. in/h ft2 F)	DENSITY (kg/m3)	CONDUCTIVITY (W/m k)			
Dimitrov, D.	1965	25.0	0.93	400.5	0.134	"method of Dr. Bock"		
II. Vermiculite Concretes								
Kluge, R.W.,	1949	23.0	0.97	368.4	0.140	guarded hot	1 x 8 x 8 in.	
Sparks, M.M.,		29.0	1.02	464.5	0.147	plate		
Tuma, E.C,		36.0	1.41	576.7	0.203			
		42.0	1.60	672.8	0.231			
Price, W.H.,	1949	49.8	1.58	797.7	0.228	guarded hot	1 x 6 in. disc.	
Cordon, W.A.		31.1	0.85	498.2	0.123	plate		
		36.4	1.15	583.1	0.166			
		50.3	1.50	805.7	0.216			
Ball, E.F.	1968	50.5	1.21	808.9	0.175	Unguarded hot		
		39.7	1.16	535.9	0.167	plate		
		30.0	0.89	480.6	0.128	British Standard		
		49.4	1.40	791.3	0.202	874:1965		
		31.4	0.82	503.0	0.118			
		24.7	0.66	395.7	0.095			
Powell, F.J.,	1971	30.9	0.98	495.0	0.141	method derived	3 x 18 x 18 in.	
Robinson, H.E.						for testing,	thick	
						heat flow meter		
Morozov (cited	1967	68.6	1.770	1,098.9	0.255			
by Lewicki)		54.9	1.330	879.4	0.192			
		37.4	1.050	599.1	0.151			
		31.2	0.890	499.8	0.128			
		19.3	0.600	309.2	0.087			
		17.5	0.560	280.3	0.081			

AUTHORS(S)	DATE	INCH-LB		SI-UNITS		TEST METHOD	SPECIMEN	REMARKS
		DENSITY (lb/ft3)	CONDUCTIVITY (Btu. in/h ft2 F)	DENSITY (kg/m3)	CONDUCTIVITY (W/m k)			
		26.8	0.810	429.3	0.117			
		24.3	0.740	389.2	0.107			
		21.2	0.670	339.6	0.097			
Kersten, M.S.	1949	33.6	1.090	538.2	0.157	guarded hot-	3 x 24 x 24 in.	
		29.6	1.060	474.1	0.153	plate		
		28.6	1.010	458.1	0.146			
		20.4	0.680	326.8	0.098			
III. Perlite Concretes								
Brouk, J.	1949	32.0	0.80	512.6	0.115	No method given		
		28.0	0.72	448.5	0.104			
		24.0	0.65	384.4	0.094			
		22.0	0.60	352.4	0.087			
		20.0	0.58	320.4	0.084			
Kluge, R.W.,	1949	21.0	0.75	336.4	0.108	guarded hot	1 x 8 x 8 in.	
Sparks, M.M.,		28.0	0.92	448.5	0.133	plate		
Tuma, E.C.		31.0	0.84	496.6	0.121			
		44.0	1.39	704.8	0.200			
		46.0	1.45	736.8	0.209			
Price, W.H.,	1949	51.0	1.72	816.9	0.248	guarded hot	1 x 6 in. disc.	
Cordon, W.A.		58.3	1.40	933.9	0.202	plate (ASTM C177-45)		
Tye, R.P.,	1976	23.7	0.735	379.6	0.106	guarded hot plate (ASTM C177 - 45)	25 to 30 mm thick	
Spinney, S.C.		23.7	0.728	379.6	0.105	heat flow meter (ASTM C518)	12 to 30 mm thick	

AUTHORS(S)	DATE	INCH-LB		SI-UNITS		TEST METHOD	SPECIMEN	REMARKS
		DENSITY (lb/ft3)	CONDUCTIVITY (Btu. in/h ft2 F)	DENSITY (kg/m3)	CONDUCTIVITY (W/m k)			
Van Geem, M.G.	1984	42.0	1.44	672.8	0.208	guarded hot-plate		
Rudnai, G.	1963	28.1	0.730	450.1	0.105			
		35.0	0.970	560.6	0.140			
Albert (cited by Lewicki)	1967	18.1	0.480	289.9	0.069			
		27.5	0.600	440.5	0.087			
		31.2	0.730	499.8	0.105			
		35.6	0.940	570.3	0.136			
Dimitrov, D.	1965	28.1	0.670	450.1	0.097	"Steady sate method of Dr. Bock"		
		49.9	1.460	799.3	0.211			
Maizel, I.L., Sukharov, M.F.	1955	62.4	1.710	999.6	0.247	Guarded hot-plate (USSR GOST 7076-54)		
		56.2	1.520	900.2	0.219			
		49.0	1.340	784.9	0.193			
		43.7	1.150	700.0	0.166			
		37.4	0.970	599.1	0.140			
		31.2	0.780	499.8	0.112			
		25.0	0.600	400.5	0.087			
Zhukov, A.V.	1962	19.7	0.590	315.6	0.085	Guarded hot-plate (USSR GOST 7076-54)	6 x 30 x 30 cm	
		20.6	0.730	330.0	0.105			
		29.3	0.840	469.3	0.121			
		30.3	0.900	485.4	0.130			
		30.3	0.970	485.4	0.140			
		34.0	0.890	544.8	0.128			
		32.5	0.910	520.6	0.131			
		46.8	1.390	749.7	0.200			
		23.7	0.590	379.6	0.085			
		30.0	0.750	480.6	0.108			
		33.1	0.880	530.2	0.127			
		39.3	1.140	629.5	0.164			
		34.3	0.970	549.4	0.140			

AUTHORS(S)	DATE	INCH-LB		SI-UNITS		TEST METHOD	SPECIMEN	REMARKS
		DENSITY (lb/ft3)	CONDUCTIVITY (Btu. in/h ft2 F)	DENSITY (kg/m3)	CONDUCTIVITY (W/m k)			
		40.6	1.210	650.3	0.175			
		49.9	1.530	799.3	0.221			
		56.2	1.840	900.2	0.265			
		54.1	1.650	866.6	0.238			
		54.6	1.640	874.6	0.237			
		52.4	1.700	839.4	0.245			
		52.9	1.590	847.4	0.229			
		49.3	1.600	789.7	0.231			
		45.6	1 390	730.4	0.200			
		43.6	1.350	698.4	0.195			
		58.7	2.050	940.3	0.296			
		56.5	1.890	905.0	0.273			
		59.3	1.890	949.9	0.273			
		54.1	1.670	866.6	0.241			
		51.2	1.590	820.1	0.229			
		44.6	1.450	714.4	0.209			
IV. Sintered or Rotary Kiln Expanded Clay, Shale or Slate Concretes (North American data)								
Kluge, R.W.,	1949	88.0	3.19	1,409.6	0.460	guarded hot	1 x 8 x 8 in.	shale
Sparks, M.M.,		95.0	4.03	1,521.8	0.581	plate		"
Tuma, E.C.		97.0	4.02	1,553.8	0.580			"
		100.0	4.08	1,601.8	0.588			"
		75.0	2.82	1,201.4	0.407			clay
		78.0	3.15	1,249.4	0.454			"
		84.0	3.39	1,345.6	0.489			"
		90.0	3.51	1,441.7	0.506			"
		73.0	2.80	1,169.3	0.404			slate
		74.0	2.80	1,185.4	0.404			"
		87.0	2.99	1,393.6	0.431			"
		85.0	3.40	1,361.6	0.490			"

AUTHORS(S)	DATE	INCH-LB		SI-UNITS		TEST METHOD	SPECIMEN	REMARKS
		DENSITY (lb/ft3)	CONDUCTIVITY (Btu. in/h ft2 F)	DENSITY (kg/m3)	CONDUCTIVITY (W/m k)			
Van Geem, M.G.	1984	94.0	4.50	1,505.7	0.649	guarded hot-plate		shale
Petersen, P.H.	1948	61.0	1.74	977.1	0.251			
		68.8	1.98	1,102.1	0.286	guarded hot plate:	1 x 8 x 8 in.	shale
		84.0	2.41	1,345.6	0.348			
Price, W.H.	1949	90.2	3.47	1,444.9	0.500	guarded hot	1 x 6 in. disc.	shale
Cordon, W.A.		93.9	4.21	1,504.1	0.607	plate		"
		103.3	4.11	1,654.7	0.593	(ASTM C177-45)		"
		104.4	3.86	1,672.3	0.557			"
Green, W.C.,	1951	70.6	2.03	1,130.9	0.293	guarded hot plate	1 x 8 x 8 in.	shale
Watstein, D.		75.0	2.27	1,201.4	0.327			"
		80.4	2.67	1,287.9	0.385			"
Rowley, F.B.,	1937	80.7	2.90	1,292.7	0.418	hot plate	2 x 24 x 24	shale
Algren, A.B.		75.0	2.57	1,201.4	0.371		in.	"
		71.7	2.50	1,148.5	0.361			"
		78.0	2.67	1,249.4	0.385			"
		72.4	2.48	1,159.7	0.358			"
		72.4	2.46	1,159.7	0.355			"
		71.0	2.41	1,137.3	0.348			"
		67.1	2.31	1,074.8	0.333			"
		67.1	2.26	1,074.8	0.326			"
		77.5	2.81	1,241.4	0.405			clay
Harmathy, T.Z.	1970	86.1	3.48	1,379.2	0.502	transient method		shale

AUTHORS(S)	DATE	INCH-LB DENSITY (lb/ft3)	INCH-LB CONDUCTIVITY (Btu. in/h ft2 F)	SI-UNITS DENSITY (kg/m3)	SI-UNITS CONDUCTIVITY (W/m k)	TEST METHOD	SPECIMEN	REMARKS
V. Sintered or Rotary Kiln Expanded Clay, and Shale Concretes (European Data)								
National Physical	1969	73.3	2.50	1,174.2	0.361	unguarded hot		clay
Lab (cited by		72.4	2.35	1,159.7	0.339	plate conforming		"
Arnold)		64.9	2.18	1,039.6	0.314	to British		"
		62.0	2.00	993.1	0.288	Standard		"
		65.8	2.19	1,054.0	0.316	874:1965		"
Ball, E.F.	1968	96.7	3.68	1,549.0	0.531	unguarded hot		shale
		85.5	3.04	1,369.6	0.438	plate		"
		76.8	2.80	1,230.2	0.375	conforming to		"
		88.6	3.21	1,419.2	0.463	British Standard		"
		92.3	3.41	1,478.5	0.492	874:1965		"
Jespersen, H.B.	1953	27.1	0.78	434.1	0.112	flat plate:	19.7 in. dia and 1.2 to 2.4 in. thick	
						hot plate:	2 in. thick	
Schule, W.,	1976	77.1	3.10	1,235.0	0.447	German	2 plates	shale
Giesecke, M.,		74.9	3.06	1,199.8	0.441	Standard	50x50x	"
Reichandt, I.		80.8	3.39	1,294.3	0.489	DIN 52612	10.5 cm	"
		65.5	2.26	1,049.2	0.326	hot plate		clay
		72.1	2.58	1,154.9	0.372			"
		79.3	2.94	1,270.3	0.424			"
Schule, W.,	1972	71.8	2.58	1,150.1	0.372	German	1,120 x	clay
Kupke, C.H.		69.9	2.70	1,119.7	0.389	Standard	1,380 x	"
		77.1	2.98	1,235.0	0.430	DIN 52612	250 mm	"
		84.2	3.23	1,348.8	0.466			"
		71.1	2.35	1,138.9	0.339			"

AUTHORS(S)	DATE	INCH-LB		SI-UNITS		TEST METHOD	SPECIMEN	REMARKS
		DENSITY (lb/ft3)	CONDUCTIVITY (Btu. in/h ft2 F)	DENSITY (kg/m3)	CONDUCTIVITY (W/m k)			
Dimitrov, D.	1965	53.0	1.70	849.0	0.245	"Steady state		clay
		57.4	1.89	919.5	0.273	method of Dr.		"
		71.1	2.30	1,138.9	0.332	Bock"		"
		103.0	4.10	1,649.9	0.591			"
Korotkevich, S.G.	1963	70.5	2.18	1,129.3	0.314	E. German "Karl		sintered shale
		68.6	2.08	1,098.9	0.300	Weiss" hot-plate		" "
		71.8	2.10	1,150.1	0.303	apparatus		" "
		66.8	2.05	1,070.0	0.296			" "
Stein, Y.S.,	1964	70.2	2.28	1,124.5	0.329	E. German "Feutron"		sintered shale
Tachkova, N.A.		83.7	2.80	1,340.7	0.404	steady-state method		" "
		101.9	3.81	1,632.3	0.550			" "
		73.6	2.47	1,179.0	0.356			" "
		88.5	3.50	1,417.6	0.505			" "
		104.7	4.46	1,677.1	0.643			" "
		75.9	2.42	1,215.8	0.349			" "
		90.3	3.39	1,587.4	0.489			" "
		99.1	3.84	1,587.4	0.554			" "
		86.9	3.44	1,392.0	0.496			" "
		98.3	4.08	1,574.6	0.588			" "
Natsievski, Y.O.	1977	62.4	2.10	999.6	0.303			clay
		77.4	2.74	1,239.8	0.395			"
		82.4	3.06	1,319.9	0.441			"
		89.2	3.63	1,428.8	0.524			sintered shale
		98.6	4.03	1,579.4	0.581			" "
		107.3	4.52	1,718.8	0.652			" "

AUTHORS(S)	DATE	INCH-LB		SI-UNITS		TEST METHOD	SPECIMEN	REMARKS
		DENSITY (lb/ft3)	CONDUCTIVITY (Btu. in/h ft2 F)	DENSITY (kg/m3)	CONDUCTIVITY (W/m k)			
Plonski, W.	1973	82.4	2.59	1,319.9	0.374			shale
		90.5	3.09	1,450.0	0.446			"
		97.3	3.55	1,559.0	0.512			"
		81.1	3.03	1,299.1	0.437			clay
		74.9	2.66	1,199.8	0.384			"
		81.1	2.93	1,299.1	0.423			"
		74.9	2.69	1,199.8	0.388			"
		56.2	1.74	900.2	0.251			"
		70.5	2.48	1,249.3	0.358			"
		78.0	2.93	1,249.4	0.423			"
		80.5	2.81	1,289.5	0.405			"
VI. Expanded Clay or Shale Concretes with Quartzitic Sand Additions								
Plonski, W.	1973	81.1	3.22	1,299.1	0.464			
		87.4	4.21	1,400.0	0.607			
		93.6	4.88	1,499.3	0.704			
		99.8	5.57	1,598.6	0.803			
Schule, W.,	1972	87.7	4.60	1,404.8	0.663	German	1120 x	Clay
Kupke, C.H.		90.8	4.68	1,454.5	0.675	Standard	1380 x	"
		98.6	4.92	1,579.4	0.710	DIN 52612	250 mm	"
		111.4	6.85	1,784.5	0.988	hot plate		"
Schule, W.,	1976	71.1	2.74	1,138.9	0.395	German	2 plates	clay
Giesecke, M.,		78.0	3.10	1,249.4	0.447	Standard	50 x 50 x	"
Reichandt, I.		86.1	3.51	1,379.2	0.506	DIN 52612	10.5 cm	"
		91.1	3.83	1,459.3	0.552	hot plate		"
		76.4	3.55	1,223.8	0.512			"

AUTHORS(S)	DATE	INCH-LB		SI-UNITS		TEST METHOD	SPECIMEN	REMARKS
		DENSITY (lb/ft3)	CONDUCTIVITY (Btu. in/h ft2 F)	DENSITY (kg/m3)	CONDUCTIVITY (W/m k)			
		83.0	3.83	1,329.5	0.552			-
		90.8	4.31	1,454.5	0.622			-
		96.1	4.43	1,539.4	0.639			-
		80.8	4.11	1,294.3	0.593			-
		88.0	4.40	1,409.6	0.635			-
		95.8	5.04	1,534.6	0.727			-
		102.3	5.48	1,638.7	0.790			-
		82.7	3.63	1,324.7	0.524			shale
		80.8	3.63	1,294.3	0.524			Shale
		86.4	3.87	1,384.0	0.558			-
		87.4	4.15	1,400.0	0.599			-
		86.7	4.31	1,388.8	0.622			-
		91.1	4.52	1,459.3	0.652			-
		92.4	5.00	1,480.1	0.721			-
		93.0	5.16	1,489.7	0.744			-
		93.0	4.92	1,489.7	0.710			-
Valore, R.C.	1953	80.2	3.26	1,284.7	0.470	guarded hot plate	1 x 8 x 8 in. plate	shale
VII. All Limestone and Sand-Limestone Concretes								
Harmathy, T.Z.	1970	129.8	10.10	2,079.2	1,457	Transient Method		
Ball, E.F.	1968	143.0	8.50	2,290.6	1.226	Unguarded hot plate conforming to British Standard 874:1965	measured in-situ	
		146.0	9.63	2,338.7	1.389			
Lentz, A.E., Monfore, G.E.	1965	126.0	10.0	2,018.3	1.442	hot-wire	4 x 4 x 8 in. prism	
		141.0	16.0	2,258.6	2.308			

AUTHORS(S)	DATE	INCH-LB		SI-UNITS		TEST METHOD	SPECIMEN	REMARKS
		DENSITY (lb/ft3)	CONDUCTIVITY (Btu. in/h ft2 F)	DENSITY (kg/m3)	CONDUCTIVITY (W/m k)			
Rowley, F.B.,	1937	135.3	8.50	2,167.3	1.226	hot plate	2 x 2 x 24 in.	
Algren, A.B.		137.8	9.30	2,207.3	1.341			
		136.4	8.90	2,184.9	1.284			
		130.1	7.80	2,084.0	1.125			
		128.0	7.20	2,018.3	1.038			
		127.3	7.30	2,039.2	1.053			
Tyner, M.	1948	113.0	6.72	1,810.1	0.969	hot plate guard	0.98 in.	
		106.0	6.12	1,698.0	0.883	ring	thick	
		118.0	6.36	1,890.2	0.917			
Lewicki, B.	1987	68.8	2.50	1,098.9	0.361			
		74.9	2.82	1,199.8	0.407			
		87.4	3.47	1,400.0	0.500			
		99.8	4.03	1,598.6	0.581			
Cammerer, W.F.,	1972	148.0	10.8	2,370.7	1.529	Hot-plate	50 x 50	
Achtziger, J.		145.0	9.5	2,322.7	1.370	W. German	x 8 cm	
		147.0	11.3	2,354.7	1.630	Standard		
		146.0	8.7	2,338.7	1.255	DIN		
		144.0	10.0	2,306.7	1.442	51612		
		145.0	9.8	2,322.7	1.413			
VIII. Aerated (Cellular) Concretes								
Dimitriu-Vilcea	1985	37.4	0.915	600.0	0.132	transient	4 x 6.5 cm	
		46.8	1.601	750.0	0.153	method	cylinder	
		25.0	0.645	400.0	0.093		(1.6 x 2.6 in)	
		31.2	0.749	500.0	0.108			

AUTHORS(S)	DATE	INCH-LB		SI-UNITS		TEST METHOD	SPECIMEN	REMARKS
		DENSITY (lb/ft3)	CONDUCTIVITY (Btu. in/h ft2 F)	DENSITY (kg/m3)	CONDUCTIVITY (W/m k)			
		25.0	0.645	400.0	0.093			
		28.1	0.700	450.0	0.101			
		31.2	0.763	500.0	0.110			
		34.3	0.887	550.0	0.128			
$ National Physical	1969	46.2	1.165	740.0	0.168	Hot-plate		
Laboratory (cited		50.0	0.134	800.0	0.191			
by Arnold)								
Laing, W.K. (cited	1969	50.0	1.220	800.0	0.176	Hot-plate		
by Arnold)		45.9	1.061	735.0	0.153			
		46.8	1.130	750.0	0.163			
		34.0	0.915	545.0	0.132			
		37.4	0.881	600.0	0.127			
		27.8	0.714	445.0	0.103			
		31.2	0.887	500.0	0.125			
		38.1	0.957	610.0	0.138			
Short, A.,		30.0	0.790	480.0	0.114			
Kinniburgh, W.								
(cited by Arnold)	1969							
Ball, E.F.	1966	51.7	1.373	828.0	0.198	unguarded hot		
		26.6	0.763	426.0	0.110	plate		
		31.1	0.846	498.0	0.122	conforming to		
		36.6	1.019	586.0	0.147	British		
		45.7	1.290	732.0	0.186	Standard		
		33.4	0.894	535.0	0.129	874:1965		
Jespersen, H.B.	1953	40.6	1.089	650.0	0.157	modified	19.7 in dia.	
		43.7	1.206	700.0	0.174	guarded	and 1.2 -	
		45.9	1.165	736.0	0.168	hot plate	2.4 in. thick	
		36.8	0.915	590.0	0.132		2 in. thick	
		27.5	0.645	440.0	0.093			

AUTHORS(S)	DATE	INCH-LB		SI-UNITS		TEST METHOD	SPECIMEN	REMARKS
		DENSITY (lb/ft3)	CONDUCTIVITY (Btu. in/h ft2 F)	DENSITY (kg/m3)	CONDUCTIVITY (W/m k)			
Hums, D.	1983	31.0	0.832	497.0	0.120	Poensgen		
		28.0	0.749	448.0	0.108	apparatus		
		37.0	0.777	592.0	0.112	(Hot-plate)		
		31.0	0.693	497.0	0.100			
		31.0	0.839	496.0	0.121			
Saare, E.,	1981	37.5	0.971	600.0	0.140	Stalhane -Pyk	5x10x20 cm	
Jansson, I.		31.2	0.811	500.0	0.117	hot wire		
		27.2	0.763	433.0	0.110			
		33.5	0.908	537.0	0.131			
Krischer, O.,	1956	40.0	1.005	640.0	0.145	stack method	edge length of	
Esdorn, H.		33.7	0.742	540.0	0.107	metal foil	specimen block	
		28.1	0.603	450.0	0.087	heaters between	is 95 mm.	
		32.4	1.130	520.0	0.163	specimens		
Dimitrov (cited	1969	25.0	0.839	400.0	0.121			
by Arnold)		28.1	0.673	450.0	0.097			
		44.9	1.387	720.0	0.200			
Jonell, P.	1961	25.0	0.610	400.0	0.088	Stalhane-Pyk	2x12x25 cm	
		31.2	0.756	500.0	0.109	hot wire		
Spooner, D.C.	1980	46.8	1.227	750.0	0.177	hot plate		
Edlind, O.	1968	25.0	0.645	400.0	0.093			
		31.2	0.804	500.0	0.116			
		40.6	1.047	650.0	0.151			
Pratt, A.W.,	1956	51.5	1.414	825.0	0.204	measuring method	12 x 12 in.	
Ball, J.M.E.		51.8	1.373	830.0	0.198	used at Building	thickness not	
						Research Station	exceeding 2 in.	
						- Guarded hot		
						plate		

AUTHORS(S)	DATE	INCH-LB		SI-UNITS		TEST METHOD	SPECIMEN	REMARKS
		DENSITY (lb/ft3)	CONDUCTIVITY (Btu. in/h ft2 F)	DENSITY (kg/m3)	CONDUCTIVITY (W/m k)			
Sandberg, P.I.	1986	37.5	1.061	600.0	0.153			
		29.6	0.693	474.0	0.100			
		31.8	0.804	510.0	0.116			
		48.1	1.206	770.0	0.174			
		31.2	0.804	500.0	0.116			
		32.2	0.763	515.0	0.110			
		30.8	0.929	493.0	0.134			
		31.3	0.804	502.0	0.116			
		30.5	0.728	488.0	0.105			
		24.3	0.624	390.0	0.090			
		29.3	0.881	470.0	0.127			
		26.2	0.742	420.0	0.107			
		20.6	0.603	330.0	0.087			
		18.7	0.555	300.0	0.080			
Loudon, A.G.	1983	30.6	0.756	490.0	0.109			
		42.6	1.012	683.0	0.146	Guarded hot-		
		47.5	1.123	761.0	0.162	plate Br. Std.		
		54.7	1.442	876.0	0.208	BS874		
Stefanski, A.	1957	18.7	0.603	300.0	0.087			
(cited by		31.2	0.763	500.0	0.110			
Lewicki)		43.7	1.262	700.0	0.182			
		56.2	1.387	900.0	0.200			
Kaufmann, B.N.	1967	13.9	0.478	223.0	0.069			
(cited by		23.0	0.659	369.0	0.095			
Lewicki)		33.8	0.783	539.0	0.113			
		34.9	0.887	559.0	0.128			
		43.7	1.290	700.0	0.186			
Makarichev, V.V.,	1973	18.7	0.645	300.0	0.093			
Levin, N.I.		25.0	0.721	400.0	0.104			

AUTHORS(S)	DATE	INCH-LB		SI-UNITS		TEST METHOD	SPECIMEN	REMARKS
		DENSITY (lb/ft3)	CONDUCTIVITY (Btu. in/h ft2 F)	DENSITY (kg/m3)	CONDUCTIVITY (W/m k)			
(cited by Plonski)		31.2	0.777	500.0	0.112			
		37.5	0.971	600.0	0.140			
		43.7	1.130	700.0	0.163			
		49.9	1.366	800.0	0.197			
Makarichev, V.V.,	1967	56.2	1.615	900.0	0.233			
Levin, N.I.		62.4	1.775	1,000.0	0.256			
(cited by		68.7	2.094	1,100.0	0.302			
Lewicki)		74.9	2.420	1,200.0	0.349			
Rudnai, G.	1963	25.0	0.603	400.0	0.087			
		31.2	0.804	500.0	0.116			
		37.5	1.019	600.0	0.147			
		43.7	1.248	700.0	0.180			
		49.9	1.449	800.0	0.209			
		62.4	1.934	1,000.0	0.279			
Plonski, W.	1973	31.2	0.832	500.0	0.120			
		37.5	1.109	600.0	0.160			
		43.7	1.248	700.0	0.180			
Belkin, A.A.	1963	74.9	2.177	1,200.0	0.314			
		58.1	1.692	930.0	0.244			
		55.6	1.615	890.0	0.233			
Lewicki, B.	1967	21.8	0.562	350.0	0.081			
		26.2	0.763	420.0	0.110			
Sergeev, A.M.,	1975	25.0	0.686	400.0	0.099	Steady state		
Dibrov, G.D.,		31.2	0.846	500.0	0.122	method		
Shmitko, E.I.		37.5	1.005	600.0	0.145			
Kovalev, S.K.		43.7	1.089	700.0	0.157			
		49.9	1.290	800.0	0.186			
		56.2	1.449	900.0	0.209			
		62.4	1.615	1,000.0	0.233			
		74.9	2.420	1,200.0	0.349			

AUTHORS(S)	DATE	INCH-LB		SI-UNITS		TEST METHOD	SPECIMEN	REMARKS
		DENSITY (lb/ft3)	CONDUCTIVITY (Btu. in/h ft2 F)	DENSITY (kg/m3)	CONDUCTIVITY (W/m k)			
IX. Siliceous Sand - Gravel Concretes								
Ball, E.F.	1968	137.0	8.66	2,194.5	1.249	unguarded hot plate conforming to British Standard 874:1965	measured in-situ	
		138.0	8.59	2,210.5	1.239			
Rowley, F.B., Algren, A.B.	1937	144.7	9.76	2,317.9	1.408	hot plate	2 in. thick	
		145.7	10.14	2,333.9	1.462			
		144.5	10.78	2,314.7	1.555			
		142.5	8.90	2,282.6	1.284			
		142.5	9.12	2,282.6	1.315			
		141.1	9.27	2,260.2	1.337			
		141.1	9.04	2,260.2	1.304			
		139.2	9.48	2,229.8	1.367			
		139.2	9.22	2,229.8	1.330			
Kluge, R.W., Sparks, M.M., Tuma, E.C.	1949	132.0	6.75	2,114.41	0.974	guarded hot plate	1 x 8 x 8 in.	
		137.0	9.57	2,210.5	1.239			
		136.0	7.94	2,178.5	1.145			
		136.0	6.20	2,178.5	0.894			
National Physical Laboratory (cited by Arnold)	1959	141.0	9.33	2,258.6	1.346	Hot-plate		
		137.9	9.12	2,208.9	1.315			
		137.0	8.93	2,194.5	1.288			
		137.9	7.65	2,208.9	1.103			
		137.9	8.42	2,208.9	1.214			
		138.8	11.28	2,223.4	1.627			
		137.9	11.00	2,208.9	1.587			
		128.9	9.50	2,064.8	1.370			
		127.9	10.30	2,048.8	1.486			
		113.9	5.76	1,824.5	0.831			
		113.9	5.57	1,824.5	0.803			

AUTHORS(S)	DATE	INCH-LB		SI-UNITS		TEST METHOD	SPECIMEN	REMARKS
		DENSITY (lb/ft3)	CONDUCTIVITY (Btu. in/h ft2 F)	DENSITY (kg/m3)	CONDUCTIVITY (W/m k)			
Van Geem, M.G.	1984	141.0	16.1	2,258.6	2.322	hot plate	2 x 1 x 16 in.	
Belkin, A.A.,	1963	149.8	8.87	2,399.6	1.279			
Valore, R.C.	1953	138.3	9.0	2,215.3	1.298	guarded hot plate	1 x 8 x 8 in.	
Mattei, J.M.,		122.6	6.79	1,963.9	0.979			
Skoda, L.F.		138.0	8.90	2,210.5	1.284			
Harmathy, T.Z.	1970	129.8	10.2	2,079.2	1.471			
		127.3	7.8	2,039.2	1.125			
Lentz, A.E.,	1965	141.0	16.0	2,258.6	2.308	hot wire	4 x 4 x 8 in.	
Monfore, G.E.		120.0	10.0	1,922.2	1.442		prism	
XI. Fired Clay								
Ball, E.F.	1968	110.0	4.3	1,762.0	0.620	unguarded hot plate conforming to British Standard 874:1965		
		127.0	5.3	2,034.3	0.764			
Cammerer, W.F. (cited by Arnold)	1959	122.0	6.1	1,954.3	0.880			
		121.1	4.5	1,939.8	0.649			
		113.9	4.15	1,824.5	0.599			
		98.9	3.95	1,584.2	0.570			
		106.7	4.6	1,709.2	0.663			

AUTHORS(S)	DATE	INCH-LB		SI-UNITS		TEST METHOD	SPECIMEN	REMARKS
		DENSITY (lb/ft3)	CONDUCTIVITY (Btu. in/h ft2 F)	DENSITY (kg/m3)	CONDUCTIVITY (W/m k)			
		101.1	3.5	1,619.5	0.505			
		98.0	3.9	1,569.8	0.562			
		93.0	4.0	1,489.7	0.577			
		91.1	2.75	1,459.3	0.397			
Jespersen, H.B.	1953	119.2	5.16	1,909.4	0.744	flat plate:	19.7 in. dia	
		104.8	4.29	1,678.7	0.619		and 1.2 to	
		87.4	3.06	1,400.0	0.441		2.4 in. thick	
		81.1	2.90	1,299.1	0.418	hot plate:	2 in. thick	
		78.6	2.58	1,259.1	0.372			
Davies, M.A., Ford, R.W.	1981	141.7	5.50	2,269.8	0.793	guarded hot box heat flux measuring plate	1.10m x 1.24m, 100 mm thick	
Kaufmann, B.N. (cited by Neusikhin, Fuchs, Garnashevich)	1964	112.8	4.03	1,806.9	0.581			
		105.7	3.23	1,693.2	0.466			
National Physical Laboratory (UK)	1948	134.8	5.50	2,159.3	0.793			
		126.7	6.40	2,029.5	0.923			
		124.2	5.80	1,989.5	0.837			
		122.3	4.10	1,959.1	0.591			
		101.7	3.70	1,629.1	0.534			
		107.3	4.70	1,718.8	0.678			
		86.7	2.60	1,388.8	0.375			
ASHRAE Handbook of Fundamentals Ch. 23	1985	120.0	5.0	1922.2	0.721	Probably based on Rowley & Algren hot-box data		
		130.0	9.0	2082.4	1.298			
Dimitrov, D.	1965	109.8	3.97	1,758.8	0.573	"Steady state method of Dr. Bock"		
		106.7	3.81	1,709.2	0.550			
		107.3	3.63	1,718.8	0.524			

AUTHORS(S)	DATE	INCH-LB DENSITY (lb/ft3)	INCH-LB CONDUCTIVITY (Btu. in/h ft2 F)	SI-UNITS DENSITY (kg/m3)	SI-UNITS CONDUCTIVITY (W/m k)	TEST METHOD	SPECIMEN	REMARKS
Krischer, O.,	1956	82.4	2.86	1,319.9	0.412	stack method,	edge length	
Esdorn, H.		99.8	3.98	1,598.6	0.574	8 specimens with	95mm	
		90.5	2.34	1,449.7	0.337	metal foil placed		
		103.0	2.90	1,649.9	0.418	between specimens		
		115.4	4.60	1,848.5	0.663			
Gray, P.E.	1982	4.0	10.3	2,306.7	1.486	Dynamic test on		
Albano, R.,		1.5	10.0	2,426.6	1.442	Joffe method		
Chesney, J.		2.3	11.2	2,439.6	1.615			
XI. Expanded Slag Concretes (North American Data)								
Kluge, R.W.,	1949	61.0	1.55	977.1	0.224	guarded hot	1 x 8 x 8 in.	
Sparks, M.M.,		72.0	1.81	1,153.3	0.261	plate		
Tuma, E.C.		79.0	2.16	1,265.4	0.312			
		84.0	2.40	1,345.6	0.346			
		76.0	1.90	1,217.4	0.274			
		89.0	2.49	1,425.6	0.359			
		94.0	2.84	1,505.7	0.410			
		101.0	3.16	1,617.9	0.456			
		81.0	2.01	1,297.5	0.289			
		86.0	2.42	1,377.6	0.349			
		90.0	2.92	1,441.7	0.421			
		105.0	3.16	1,681.9	0.456			

AUTHORS(S)	DATE	INCH-LB		SI-UNITS		TEST METHOD	SPECIMEN	REMARKS
		DENSITY (lb/ft3)	CONDUCTIVITY (Btu. in/h ft2 F)	DENSITY (kg/m3)	CONDUCTIVITY (W/m k)			
Peterson, P.H.	1948	61.5	1.57	985.1	0.226			
		71.4	1.93	1,143.7	0.278	guarded	1 x 8 x 8 in.	
		94.4	2.82	1,512.1	0.407	hot plate		
Rowley, F.B.,	1937	74.6	1.91	1,195.0	0.275	hot plate	2 x 24 x 24 in.	
Algren, A.B.								
Price, W.H.	1949	91.6	2.55	1,467.3	0.368	guarded hot	1 x 6 in. disc.	
Cordon, W.A.		83.3	2.64	1,334.3	0.381	plate conforming		
						to ASTM C-177-45		
Foran, M.R.,	1953	84.7	2.42	1,356.8	0.349			
Ball, S.		96.0	2.80	1,537.8	0.404			
Johnson, R.E.,								
Wallace, J.R.								
Lewis, D.W.	1958	60.0	1.50	961.1	0.216	guarded hot	1.25 x 12 x 12 in.	
		68.0	1.74	1,089.3	0.251	plate		
		73.1	2.17	1,170.9	0.313	conforming to		
		79.8	2.25	1,278.3	0.325	ASTM C177		
		87.0	2.37	1,393.6	0.342			
		87.9	2.41	1,408.0	0.348			
		96.3	2.74	1,542.6	0.395			
		103.4	3.19	1,658.3	0.460			
		98.3	2.91	1,574.8	0.420			
		95.2	2.82	1,525.0	0.407			
		85.7	2.40	1,372.8	0.346			
		79.9	2.12	1,279.9	0.306			
		86.0	2.44	1,377.8	0.352			
		97.8	2.83	1,563.4	0.408			
Green, W.C.,	1951	75.0	1.92	1,201.4	0.277	guarded hot	1 x 8 x 8 in.	
Watstein, D.		79.0	2.19	1,265.5	0.316	plate		
		84.0	2.46	1,345.6	0.355			

AUTHORS(S)	DATE	INCH-LB		SI-UNITS		TEST METHOD	SPECIMEN	REMARKS
		DENSITY (lb/ft3)	CONDUCTIVITY (Btu. in/h ft2 F)	DENSITY (kg/m3)	CONDUCTIVITY (W/m k)			
XI. Expanded Slag Concretes (European Data)								
National Physical Laboratory UK (cited by Arnold)	1969	64.0	1.42	1,025.2	0.205	unguarded hot plate conforming to British Standard 874:1965		
		73.9	1.93	1,183.8	0.278			
		83.9	2.39	1,343.9	0.345			
Pratt, A.W., Ball, J.M.E.	1958	86.7	2.19	1,388.8	0.316	guarded hot plate	12 x 12 in. thickness not to exceed 2 in.	
		80.8	2.30	1,294.3	0.332			
		81.1	1.94	1,299.1	0.280			
		81.1	2.06	1,299.1	0.297			
		69.9	1.62	1,119.7	0.234			
Ball, E.F.	1968	112.0	4.68	1,794.1	0.675	unguarded hot plate conforming to British Standard 874:1965		
		105.0	3.39	1,681.9	0.489			
		114.2	4.59	1,829.3	0.662			
		108.9	3.54	1,744.4	0.511			
		83.0	2.18	1,329.5	0.314			
		84.9	2.07	1,360.0	0.299			
		82.1	2.17	1,315.1	0.313			
		89.1	2.65	1,427.2	0.382			
Spooner, D.C.	1980	87.4	2.66	1,400.0	0.384	unguarded hot plate		
Plonski, W.	1973	62.4	1.87	999.6	0.270			
		68.8	2.29	1,098.9	0.330			
		78.0	2.77	1,249.4	0.400			
		83.6	3.05	1,339.1	0.440			
		91.1	2.72	1,459.3	0.392			
		93.8	2.80	1,499.3	0.404			
		112.9	3.70	1,808.5	0.534			
		114.8	3.29	1,838.9	0.475			

AUTHORS(S)	DATE	INCH-LB		SI-UNITS		TEST METHOD	SPECIMEN	REMARKS
		DENSITY (lb/ft3)	CONDUCTIVITY (Btu. in/h ft2 F)	DENSITY (kg/m3)	CONDUCTIVITY (W/m k)			
		116.1	3.59	1,859.7	0.518			
		83.0	1.87	1,329.5	0.270			
		87.4	2.29	1,400.0	0.330			
		93.6	2.91	1,499.3	0.420			
		106.1	3.68	1,699.6	0.531			
		118.6	5.13	1,899.8	0.740			
Grigoriev, V.C.	1963	62.4	1.86	999.6	0.268			
		74.9	2.26	1,199.8	0.326			
		87.4	2.82	1,400.0	0.407			
		99.8	3.31	1,598.6	0.477			
Natsievski, Y.D.	1977	91.7	2.82	1,468.9	0.407			
		101.7	3.07	1,629.1	0.443			
		111.1	3.63	1,779.7	0.524			
		84.9	2.58	1,360.0	0.372			
		93.6	2.74	1,499.3	0.395			
		102.3	3.15	1,638.7	0.454			
		95.5	2.98	1,529.8	0.430			
		103.0	3.23	1,649.9	0.468			
		110.5	3.71	1,770.0	0.535			
		87.4	2.82	1,400.0	0.407			
		94.8	2.98	1,518.6	0.430			
		101.1	3.15	1,619.5	0.454			
Spivak, N.,	1977	101.6	2.88	1,627.5	0.415			
Gryzlov, V.S.		98.3	2.90	1,574.6	0.418			
		98.5	3.07	1,577.8	0.443			
		118.2	4.24	1,893.4	0.612			
		119.6	4.22	1,915.8	0.609			

AUTHORS(S)	DATE	INCH-LB		SI-UNITS		TEST METHOD	SPECIMEN	REMARKS
		DENSITY (lb/ft3)	CONDUCTIVITY (Btu. in/h ft2 F)	DENSITY (kg/m3)	CONDUCTIVITY (W/m k)			
Kaufmann, B.N. (cited by Lewicki)	1967	98.6	2.96	1,579.4	0.427			
Ushkov, F.V., Tachkova, N.A., Morozov, N.V. (cited by Lewicki)	1967	81.1	2.38	1,299.1	0.343			
Rudnai, G.	1963	71.8	1.69	1,150.1	0.244			
		78.0	1.94	1,249.4	0.280			
		88.6	2.42	1,419.2	0.349			
		91.7	2.66	1,468.9	0.384			
		96.1	2.90	1,539.4	0.418			
		101.1	3.31	1,619.5	0.477			
XIII. Cinder and Sintered Fly Ash Concrete								
Kluge, R.W., Sparks, M.M., Tuma, E.C.	1949	79.0	2.19	1,265.5	0.316	guarded hot plate	1 x 8 x 8 in	Sintered fly ash
		82.0	2.80	1,313.5	0.404			" " "
		89.0	2.88	1,425.6	0.415			" " "
		93.0	3.11	1,489.7	0.449			" " "
National Physical Lab (UK) (cited by Arnold)	1969	83.9	2.69	1,343.9	0.388	unguarded hot plate conforming to British Standard 874:1965		cinder
		103.0	4.17	1,649.9	0.601			"
		78.9	2.82	1,263.9	0.407			"
		83.0	3.29	1,329.5	0.475			"
		88.9	3.37	1,424.0	0.486			"

AUTHORS(S)	DATE	INCH-LB		SI-UNITS		TEST METHOD	SPECIMEN	REMARKS
		DENSITY (lb/ft3)	CONDUCTIVITY (Btu. in/h ft2 F)	DENSITY (kg/m3)	CONDUCTIVITY (W/m k)			
Laing, W.K (cited by Arnold)	1969	73.0	1.99	1,169.3	0.287	Hot-plate		Sintered fly ash
		85.5	2.67	1,369.6	0.385			" " "
		66.2	1.71	1,060.4	0.247			" " "
		93.9	2.95	1,504.1	0.425			" " "
		96.4	2.96	1,544.2	0.427			" " "
		81.8	2.57	1,310.3	0.371			" " "
		84.3	2.68	1,350.4	0.387			" " "
		74.9	2.42	1,199.8	0.349			" " "
		101.1	3.28	1,619.5	0.473			" " "
Rowley, F.B., Algren, A.B.	1937	103.6	3.53	1,659.5	0.509	hot plate	2 x 24 x 24 in.	cinder
		98.7	3.41	1,581.0	0.492			"
		92.0	2.94	1,473.7	0.424			"
		101.4	3.44	1,624.3	0.496			"
		94.0	3.08	1,505.7	0.444			"
		94.4	3.07	1,512.1	0.443			"
Ball, E.F.	1968	92.9	3.67	1,488.1	0.529	unguarded hot plate conforming to British Standard 874:1965		Sintered fly ash
		88.5	2.98	1,417.6	0.430			" " "
		76.7	2.07	1,228.6	0.299			" " "
Rudnai, G.	1963	68.6	1.77	1,098.9	0.255			cinder
		79.3	2.58	1,270.3	0.372			"
		81.8	2.82	1,310.3	0.407			"
		84.3	3.07	1,350.4	0.443			"
		87.4	3.31	1,400.0	0.477			"
		92.4	3.87	1,480.1	0.558			"

AUTHORS(S)	DATE	INCH-LB		SI-UNITS		TEST METHOD	SPECIMEN	REMARKS
		DENSITY (lb/ft3)	CONDUCTIVITY (Btu. in/h ft2 F)	DENSITY (kg/m3)	CONDUCTIVITY (W/m k)			
Kaufmann, B.N.	1955	74.3	2.18	1,190.2	0.314			Cinder
Lewicki, B.	1967	90.5	3.19	1,449.7	0.460			Cinder
		78.6	2.32	1,259.1	0.335			"
		97.3	3.77	1,558.6	0.544			"
		81.1	2.41	1,299.1	0.348			"
		62.4	1.85	999.6	0.267			"
		68.6	2.26	1,098.9	0.326			"
		74.9	2.66	1,199.8	0.384			"
		78.0	2.74	1,249.4	0.395			"
		84.3	3.07	1,350.4	0.443			"
		90.1	3.39	1,443.3	0.489			"

XIV. Microporous Calcium Silicate (Microporite, Light Lime Concrete; Autoclave Cured)

Schlegel, E.,	1984	15.0	0.416	240.0	0.060
Schaarschmidt, G.		15.6	0.423	250.0	0.061
		15.6	0.423	250.0	0.061
		21.8	0.548	350.0	0.079
		25.0	0.555	400.0	0.080
		21.8	0.548	350.0	0.079
		37.5	0.901	600.0	0.130
		20.0	0.506	320.0	0.073
		14.4	0.402	230.0	0.058
		13.1	0.381	210.0	0.055
		15.0	0.416	240.0	0.060
		25.0	0.610	400.0	0.088
		10.6	0.333	170.0	0.048

AUTHORS(S)	DATE	INCH-LB		SI-UNITS		TEST METHOD	SPECIMEN	REMARKS
		DENSITY (lb/ft3)	CONDUCTIVITY (Btu. in/h ft2 F)	DENSITY (kg/m3)	CONDUCTIVITY (W/m k)			
		12.5	0.367	200.0	0.053			
		31.2	0.645	500.0	0.093			
Lewicki, B.	1967	74.9	1.657	1,200.0	0.239			
		31.2	0.659	500.0	0.095			
		37.5	0.860	600.0	0.124			
		56.2	1.269	900.0	0.183			
		34.3	0.804	550.0	0.116			
		40.6	1.615	650.0	0.233			
		59.3	2.260	950.0	0.326			
		62.4	2.018	1,000.0	0.291			
		81.2	2.420	1,300.0	0.349			
		72.4	2.018	1,160.0	0.291			
		76.2	2.260	1,220.0	0.326			
Graf, O.	1949	28.1	0.562	450.0	0.081			
		48.7	1.102	780.0	0.159			
		69.9	1.782	1,120.0	0.257			
XV. Expanded Polystyrene Bead Concrete								
Hohwiller, F.,	1968	12.5	0.415	200.2	0.060	German		
Kohling, K.		13.4	0.473	214.6	0.068	Standard		
		18.7	0.588	299.5	0.085	DIN 52612		
		19.0	0.628	304.4	0.091	Blatt 1,		
		21.2	0.680	339.6	0.098	DIN 52612		
		24.1	0.709	386.0	0.102	Blatt 2		
		24.7	0.815	395.7	0.118			
		30.5	0.863	488.6	0.124			
		31.2	0.855	499.8	0.123			
		33.2	1.070	531.8	0.154			
		34.6	1.020	554.2	0.147			

AUTHORS(S)	DATE	INCH-LB DENSITY (lb/ft3)	INCH-LB CONDUCTIVITY (Btu. in/h ft2 F)	SI-UNITS DENSITY (kg/m3)	SI-UNITS CONDUCTIVITY (W/m k)	TEST METHOD	SPECIMEN	REMARKS
		37.4	1.000	599.1	0.144			
		37.4	1.150	599.1	0.166			
		41.4	1.210	663.2	0.175			
		50.6	1.650	810.5	0.238			
		54.7	1.650	876.2	0.238			
		62.0	2.020	993.1	0.291			
XVI. Pumice and Sintered or Rotary Kiln Expanded Clay and Shale No-Fines Concretes								
Valore, R.C.,	1953	53.4	1.680	855.4	0.242	guarded	1 x 8 x 8 in.	pumice
Mattei, J.M.,		48.2	1.450	772.1	0.209	hot plate	plate	"
Skoda, L.F.		47.8	1.600	765.7	0.231			"
		47.8	1.590	765.7	0.229			"
		50.4	1.650	807.3	0.238			"
		46.7	1.440	748.1	0.208			"
		45.2	1.480	724.0	0.213			Pumice
		45.8	1.400	733.6	0.202			"
		40.5	1.260	648.7	0.182			"
		44.4	1.370	711.2	0.198			"
		81.1	3.020	1,299.1	0.436			Rotary kiln shale
		73.0	2.600	1,169.3	0.375			" " "
		70.2	2.500	1,124.5	0.361			" " "
		72.6	2.490	1,162.9	0.359			" " "
		65.2	1.930	1,044.4	0.278			" " "
		72.0	2.470	1,153.3	0.356			" " "
		79.3	3.070	1,270.3	0.443			Sintered shale
		77.1	2.710	1,235.0	0.391			" "
		73.7	2.700	1,180.6	0.389			" "
		67.1	2.070	1,074.8	0.299			" "

AUTHORS(S)	DATE	INCH-LB		SI-UNITS		TEST METHOD	SPECIMEN	REMARKS
		DENSITY (lb/ft3)	CONDUCTIVITY (Btu. in/h ft2 F)	DENSITY (kg/m3)	CONDUCTIVITY (W/m k)			
Istkovich, S.K.	1977	37.1	1.21	594.3	0.175			Sintered shale
		36.2	1.23	579.9	0.177			" "
		31.8	1.10	509.4	0.159			" "
		32.1	1.03	514.2	0.149			" "
		32.3	1.06	517.4	0.153			" "
		31.6	1.05	506.2	0.151			" "
		30.6	0.95	490.2	0.137			" "
		27.8	0.95	445.3	0.137			" "
Natsievski, Y.D.	1977	56.8	1.69	909.8	0.244			Clay
		64.3	2.10	1,030.0	0.303			"
		72.4	2.40	1,159.7	0.346			"
		74.3	2.82	1,190.2	0.407			Sintered shale
		82.4	3.23	1,319.9	0.466			" "
		88.6	3.37	1,419.2	0.486			" "
Kristen,	1973	54.3	1.23	869.8	0.177			Clay
Czech (cited		40.6	1.21	650.3	0.175			"
by Plonski)								
Stein, Y.S.,	1964	55.0	1.39	881.0	0.200	E. German		Sintered shale
Tachkova, N.A.		71.0	2.42	1,137.3	0.349	"Feutron"		" "
		80.3	2.29	1,286.3	0.330	Steady-state method		" "

Appendix C

MOISTURE CONTENT AND THERMAL CONDUCTIVITY IN TENNESSEE TECHNOLOGICAL UNIVERSITY STUDIES OF THERMAL CONDUCTIVITY OF PERLITE BLOCK AND STRUCTURAL CONCRETES

Theses of M.A. Wilson (1984) and R.D. Haynes (1986) under the supervision of Professor D.W. Yarbrough, Ph.D.

The theses of Wilson and Haynes are discussed here not only for their intrinsic value in using two testing procedures not usually employed in thermal conductivity tests of concrete, but also because they are illustrative of problems frequently encountered in assessing the effect of moisture contents upon thermal conductivity of portland cement products in general and lightweight concretes in particular.

Description of Test Specimens: Tests were performed by Wilson and Haynes on air-dry perlite concretes by use of a screen-heater unguarded hot-plate and a radial heat flow method, respectively. The concretes used in these studies differ from conventional lightweight aggregate concretes in several respects:

(a) Cement contents of conventional block concretes range form about 300 to 400 lb/cu. yd. (178 to 237 kg/m^3); for structural and insulating concretes cement contents range form 400 to 750 lb/cu. yd. (237 to 445 kg/m^3).

Cement contents were 757 to 950 lb/cu. yd. (445 to 564 kg/m^3) for Wilson's block concretes, and 1033 to 1502 lb/cu.yd. (613 to 891 kg/m^3) for the Haynes structural concretes. Such high cement contents would be unattractive economically, and creep and drying shrinkage would be unfeasibly high due to very low density and very low modulus of elasticity of the perlite aggregate.

(b) Cement paste weight fractions are calculated as 1.2 pc/(1.2 pc + a), where pc is weight of portland cement, a is the weight of aggregate, and the factor 1.2 accounts for 20 percent combined water, by weight of cement, in hardened concrete. For conventional block mixtures, average cement paste fractional weights are about 0.09 to 0.12 for sand-gravel, 0.13 to 0.17 for expanded shale, and 0.20 to 0.26 for pumice concretes.

Fractional weights of cement paste are about 0.70 to 0.88 for Wilson concretes, and 0.73 to 0.87 for Haynes concretes.

It can be stated that (1) the Wilson and Haynes studies involved

the use of perlite aggregates not only in masonry units, but also in structural concrete, for which perlite aggregates are not particularly suited; and that 2) their concretes do not have a typical composition. Nonetheless, this does not detract from the merits of their work. To the contrary, the thermal conductivities reported are valuable in validating calculation techniques for oven-dry thermal conductivities and moisture correction factors (Valore, 1987 IMI report), by presenting values outside customary ranges.

Moisture Effect on Thermal Conductivity: As will be shown, Wilson's air-dry thermal conductivity data appear to be of excellent consistency, and correlate very well with oven-dry thermal conductivity estimates obtained by Valore (1987), when oven-dry values are corrected for moisture content. Relationships are shown in Figure C.1 for thermal conductivity test data for air dry concretes, and thermal conductivity values are also calculated by the Valore equation for oven-dry concretes. This equation relates thermal conductivity to density for oven-dry perlite concretes. The rule-of-thumb given by Valore for moisture correction (1980 and 1956) is to increase thermal conductivity values obtained for oven-dry concretes by 4 to 6 percent for each one percent of moisture by weight. The moisture correction factors are obtained as follows:

The amount of evaporable water in concrete is essentially proportional to the cement paste fractional weight only, when at moisture equilibrium at constant relative humidity (e.g., 60 percent). Average cement paste fractional weights are about 0.80 +/- 0.07 for both Wilson and Haynes concretes and 0.09 to 0.26 for most other concretes. It can therefore be seen that the moisture contents of the perlite concretes will be much higher than those of conventional block and structural concretes. Sorbed moisture in normal weight concretes is of the order of one percent at 60 percent relative humidity and increases as density of concrete decreases (as fractional cement paste weight increases). Equilibrium moisture contents taken from the Powers and Brownyard curve of Fig 3.18 for 0.58 water/cement ratio cement paste are estimated at 8 percent for Wilson's steam-cured blocks and 10.7 percent for the Haynes moist-cured concretes. Thermal conductivity moisture factors are estimated at 5.0 and 5.5 percent increase per one percent increase in moisture content, by weight, for steam-cured and moist-cured concretes respectively. The thermal conductivity moisture corrections for the two concrete types are therefore:

Wilson concretes moisture factor:

$1 + (0.8 \times 8 \times 0.05) = 1.32$, taken approximately as 1.35

Haynes concretes:

$1 + (0.8 \times 10.7 \times 0.055) = 1.47$, taken approximately as 1.5

Multiplying these factors (1.35 and 1.50) by calculated thermal conductivity values for oven-dry perlite concrete (Valore,

1987) yields values in good agreement with respective Wilson and Haynes values. Conversely, dividing experimental values by these factors provides estimates of the thermal conductivity of these concretes in an oven-dry condition.

These results are partly fortuitous. The oven-dry densities after the prolonged testing sequence are not known. Atmospheric carbonation would increase dry densities markedly due to combination of CO_2 with calcium compounds in the cement paste. While density increased due to formation of solid calcium carbonate, the moisture might be unaffected. The discrepancy might not be large and could be eliminated by performing oven drying and moisture content determination after final thermal conductivity measurements.

Haynes determined relationships of thermal conductivity to moisture contents over periods in excess of 100 days. Some curves were concave upward, indicating effects of progressive carbonation, since the specimens were losing weight due to loss of moisture and gaining weight due to carbonation at the same time. Since this process was not accounted for in calculations, it resulted in inordinately low moisture factors. Tye and Spinney (1976) showed a similarly low moisture factor (2.2 percent increase in thermal conductivity per one percent increase in moisture content, by weight) for a low density perlite concrete. On the other hand, Van Geem, Fiorato, and Musser (1982) obtained a mean moisture factor for a 46 pcf (737 kg/m^3) perlite concrete of 4.1 percent increase in thermal conductivity per one percent increase in moisture content, by weight, by using a hot-wire method. The USSR Code SNiP II-3-79 (1986) lists factors of 5 to 7 percent per one percent of moisture for perlite concretes weighing 75 to 37 pcf (1200 to 600 kg/m^3), respectively, while Zhukov (1962) lists a value of 2.5 percent per one percent. This would appear to be a fruitful area for new research in order to resolve these contradictions. Meanwhile, the rule of thumb of 4 to 6 percent thermal conductivity increase per one percent of moisture (by weight) appears to be valid for lightweight concretes generally. For normal weight concretes the moisture factor is higher. (Various studies indicate moisture factors of 7% to 15%. Calculations for limestone concretes by Valore indicate a value of 7%, and for siliceous aggregate concretes of 9%. More research is needed.) However, equilibrium moisture contents are much lower in normal weight concretes (e.g. 1% to 2% for dense concretes) vs. lightweight concretes (e.g. 2% to 4% for expanded shale concretes).

Recommendations: It is recommended that the data of Wilson and Haynes be recast for publication, augmented by additional thermal conductivity tests of the Haynes radial heat flow specimens, now over two years old, with new determinations of oven-dry density and thermal conductivity in the present air-dry and the oven-dry states. The expanded shale blocks should also be retested. Moisture contents were not provided for these concretes.

It is also urged that the screen-heater test method used by Wilson be employed in a major investigation of masonry units, including small, single wythe assemblages of solid bricks and blocks,

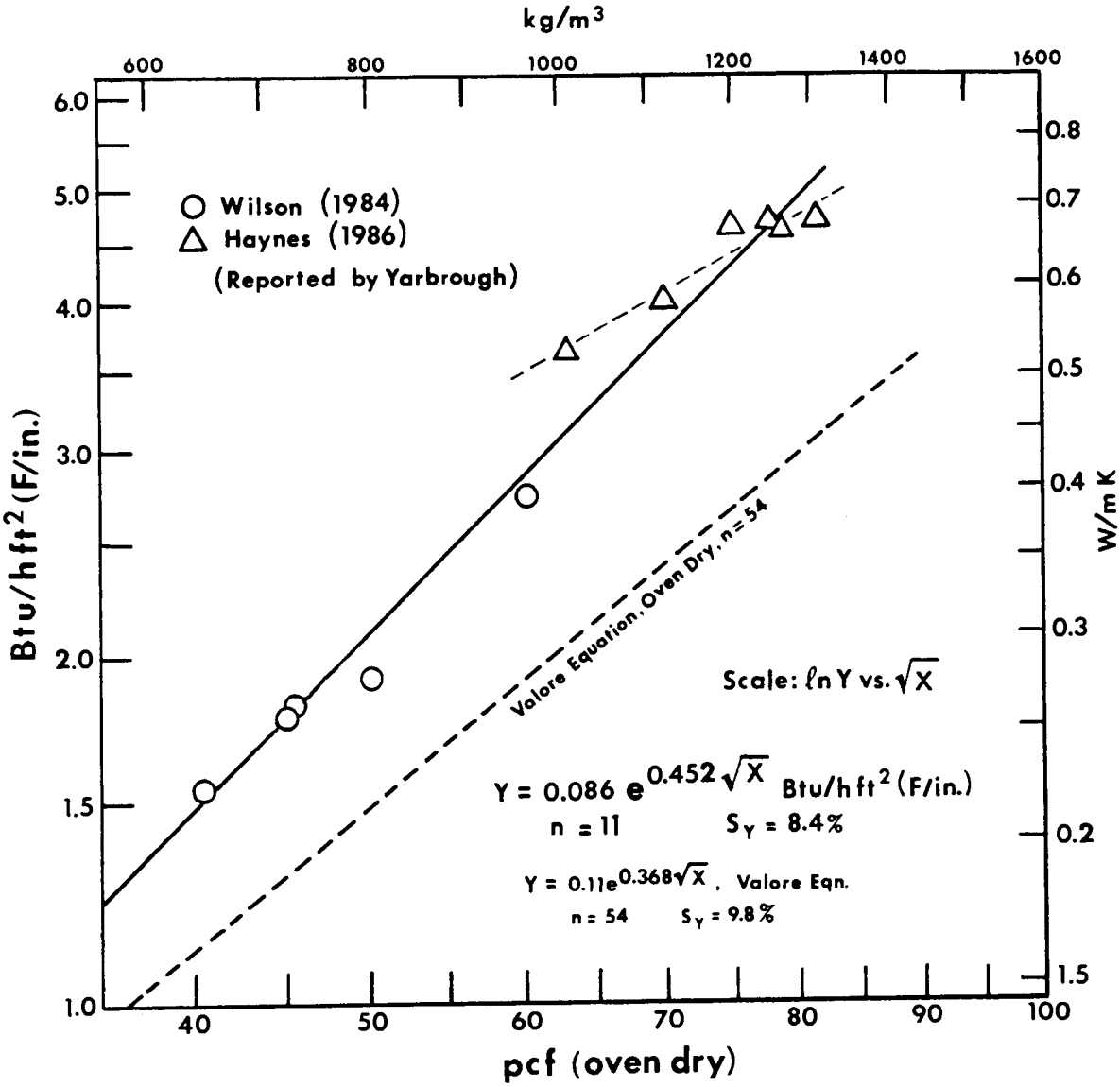
to determine the effects of moisture and atmospheric carbonation on density and thermal conductivity. The whole range of lightweight block concretes should be included, with and without supplementary natural aggregate such as quartzitic, carbonate, and granitic fine aggregates. The specimens used by Wilson are quite satisfactory; they should be accumulated now and stored in the real world -- outdoors -- for later testing.

Limitations of the hot-plate test, ASTM C177, have been partially overcome in evaluating the effects of "normal moisture" in concrete on thermal conductivity by using small temperature gradients. The rapid hot-wire method has also been used, but does not appear to be suitable for concretes with coarse aggregates. That limitation may not apply to perlite, vermiculite, and expanded polystyrene bead concretes or to neat cement pastes. The screen heater hot-plate should be tried for these materials, probably at low temperature gradients. This method should also be used to evaluate the effects of moisture on the effective thermal conductivity of granular insulating fills. Very little data exist for effects of moisture in perlite, vermiculite, and expanded clay and shale fills.

Oven dry density and moisture contents of concrete can easily be estimated by calculation when proportions of dry constituents of concretes (including water of cement hydration), and density of freshly mixed concrete are accurately known. Equilibrium moisture contents at a given relative humidity can also be estimated for structural concretes of relatively low air permeabililty. Block concretes with "open" textures attain a high degree of carbonation within a year or two of dry storage. In real structures, the degree of carbonation of some lightweight blocks can be high. The opposing influences of higher density and possibly reduced moisture contents on thermal conductivity which appear to have been present in the Haynes study need to be investigated further.

FIG. C.1

DENSITY – THERMAL CONDUCTIVITY RELATIONSHIP FOR AIR-DRY PERLITE CONCRETE TESTS AT THE TENNESSEE



Appendix D

EFFECT OF LACK OF PLANENESS OF HOT PLATE TEST SPECIMENS ON MEASURED THERMAL CONDUCTIVITY

Small air-gaps between concrete specimen surfaces and hot and cold-plate surfaces can cause large errors in measured thermal conductivity. The errors decrease with specimen thickness and increase with the "true" thermal conductivity of the specimen. For example, a normal weight concrete specimen with quartizitc sand and gravel aggregates could have a true thermal conductivity of 13 Btu/h-ft^2-(F/in.), (1.87 W/m-K). For a specimen one inch thick (25.4 mm) and an average air-gap of 0.001 in (0.025 mm), assuming a thermal conductivity for air of 0.173 (0.025), the thermal resistance of two air-gaps is 0.002/0.173 = 0.0116 h-ft^2-F/Btu (0.002 m^2-K/W); the resistance of the specimen, one inch thick, is 1/13 = 0.077 (0.0135). The measured resistance is 0.077 + 0.0116 = 0.0886; the error due to the air gaps is 0.0116/0.077, i.e., + 0.151 or +15 percent; the measured thermal conductivity is 11.3 versus the true thermal conductivity of 13; the measured thermal conductivity is in error,, and is low by 13 percent. The following table shows measuring errors in tests of oven-dry concrete specimens of various densities, one and two inches thick, for combined air-gaps of 0.002 inch.

TABLE D.1 MEASURING ERRORS DUE TO AIR GAPS BETWEEN TEST SPECIMEN AND THERMOCOUPLE JUNCTIONS

True Thermal conductivity Btu/h-ft^2-(F/in.)	Dry Density pcf	Thermal conductivity Measuring Error for Specimen Thickness of: 1 inch	2 inches
13	140	-13.1%	-7.0%
5	97	- 5.5	-2.8
3	83	- 3.4	-1.7
1.50	50	- 1.7	-0.9
0.75	27	- 0.9	-0.45

This table shows that errors due to lack of planeness are small for light weight concretes tested in 2-inch thicknesses, as has been done in Europe since 1960. For normal weight concretes, testing of 3 or 4 inch thick specimens, if practicable, would be preferred. The average air-gap of 0.001 inch, used in the above calculations, is not easy to achieve for normal weight concretes. Calculations of thermal conductivity of such concretes, by the Cubic Model equation, based on conductivities of aggregates and cement pastes is the authors' preferred alternative to testing.

Appendix E

EFFECT OF MOISTURE CONTENT ON THERMAL CONDUCTIVITY OF CONCRETE

Valid comparisons of thermal conductivities obtained in two or more tests of the same masonry material by the same or different test methods can only be made for the same moisture content. Hot-plate tests are usually done on oven-dry specimens, dried to constant weight at 220 to 230 F (105 to 110 C), while hot-box tests are done on specimens "conditioned" in laboratory air for weeks or months. In the latter case evaporable (free) moisture will be present, depending on the thickness and cement content of solid sections of material and the temperature and relative humidity of laboratory air.

Valid comparisons of thermal conductivities derived from hot-plate and hot-box tests require that values be corrected to a common moisture content; in this case it is required that hot-box data be corrected to the oven-dry condition. Moisture "correction factors" proposed by Valore (1956, 1980) are 3.5 to 6 percent increase in thermal conductivity for each one percent of moisture, by weight, for light weight concretes and 7 to 9 percent for normal weight concretes. These factors have been verified in Valore's recent International Masonry Institute (1987) report. The average moisture factor in the 1986 USSR standard SNiP II-3-79 for all types of light weight concretes is 5 percent per one percent of moisture by weight. More recently Loudon (1983) verified the validity of Valore's method of correcting thermal conductivity for moisture in tests in the U.K. of aerated and expanded slag concretes and has called for revision of the present CIBS Guide (1980) to incorporate similar thermal conductivity moisture factors.

For the present report moisture factors of 5.0 and 4.0 percent are used for correcting thermal conductivities of perlite and expanded clay or shale concretes, respectively, to the oven-dry condition. These values can also be used to estimate "practical" thermal conductivity values based on established equilibrium moisture contents in relation to mean relative humidities for particular exposure conditions. For normal weight concretes moisture factors of 7 percent and 9 percent apply to concretes with carbonate and quartzitic aggregates, respectively, per one percent of moisture, by weight. The "practical" thermal conductivity can be 15 to 40 percent higher than an oven-dry value, depending on the masonry material and exposure conditions, and indicates that the use of oven-dry thermal conductivity values in the ASHRAE Handbook of Fundamentals (Chapter 23, 1985) as "design" values, is in need of revision. Valore's values also show the errors involved in the use of the Jakob (1949) correction factors in such European codes as those of the U.K., France, and other countries, which call for increasing oven-dry thermal conductivity values by 30, 60, and 75 percent for moisture contents of 1.0, 3.0 and 5.0 percent by volume respectively.

Appendix F

EFFECT OF SIZE AND SHAPE OF AIR-SPACES ON THEIR THERMAL RESISTANCE

Anderson (1968) showed that the resistance of a small air-space depends not only on its thickness in the direction of heat flow, but also on its horizontal length perpendicular to heat flow. Anderson shows that, for an air space of small thickness (2 inches, 50 mm or less) its resistance increases as its length decreases, and the traditional R-value of an air space of approximately 1.0 (0.176) is used only for those spaces whose length and thickness are large, as in North American blocks, or for thin air spaces greater than one inch (25 mm) thick whose length exceeds four inches (100 mm). Anderson's R-values for air spaces are incorporated as "standard" values in the present British CIBS Guide (1980). For North American large-core blocks the traditional R-value of core spaces is used, with the possible exception of nominal four-inch hollow units.*

The main application of Anderson's R-values is to European types of multicore concrete blocks and "multi-perforated" fired clay blocks which have numerous rows of small cores or slots closed at tops and bottoms. (Austrian and German clay blocks have up to 20 and concrete blocks up to 10 rows of slots in 12 in. or 300 mm thick units.) R-values of one inch vertical spaces of square section are about 30 percent higher than traditional values.

Thermal resistances of air spaces from Table A 3.7 of Part A3 of the UK CIBS Guide (1980) are given in Table F.1 below, in h-ft^2-F/Btu (m^2-K/W).

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* The "traditional" R-value of air spaces < 0.75 in (10 mm) is taken from the 1985 ASHRAE Handbook of Fundamentals, Chapter 23, Table 2.4, for a mean temperature of 50F (10C). This value may depart appreciably from actual R-values of spaces similar in size, shape and orientation to cores in masonry units under certain conditions, according to Shipp (1983). [Ref.: Shipp, P.H., (1983). "Natural Convection Within Masonry Block Walls", ASHRAE Transactions, vol. 89, Part 1, 14 pp.]

TABLE F.1 THERMAL RESISTANCE OF AIR SPACES

Length of Air-Space	Thickness of Air-Space, in. (mm) 0.20 in. (5 mm)	0.28 in. (7 mm)	0.39 in. (10 mm)	0.59 in. (15 mm)	0.99 in. (25 mm)	>1.0 in. (>25 mm)
0.39 in. (10 mm)	0.63 (0.11)	0.80 (0.14)	0.97 (0.17)	1.19 (0.21)	1.36 (0.24)	1.53 (0.27)
0.79 in. (20 mm)	0.63 (0.11)	0.74 (0.13)	0.91 (0.16)	1.08 (0.19)	1.25 (0.22)	1.36 (0.24)
1.97 in. (50 mm)	0.63 (0.11)	0.74 (0.13)	0.85 (0.15)	1.02 (0.18)	1.08 (0.19)	1.19 (0.21)
3.94 in. (100 mm)	0.57 (0.10)	0.68 (0.12)	0.80 (0.14)	0.97 (0.17)	1.02 (0.18)	1.14 (0.20)
>7.87 in. (>200 mm)	0.57 (0.10)	0.68 (0.12)	0.80 (0.14)	0.91 (0.16)	0.97 (0.17)	1.02 (0.18)

Multiply R values in U.S. units by 0.176 to convert to SI units, m^2-K/W

Anderson's equation for R of small air-spaces in SI units is:

$$R = \frac{1}{\max(0.025/a \text{ or } 0.92) + 2.315\,[1 + (1 + a^2/a'^2)^{0.5} - a/a']}$$

where "max" means the larger of the values in parentheses, a is the thickness of the air space, and a' is the length of the space in metres; 0.025 is the thermal conductivity of air in W/m-K.

In U.S. units:

$$R = \frac{1}{\max(0.173/a \text{ or } 0.162) + 0.407\,[1 + (1 + a^2/a'^2)^{0.5} - a/a']}$$

where a and a' are in inches.

Appendix G

The Modified Cubic Model

The "Modified" Cubic Model is generally used to calculate the effective thermal conductivity of a composite of rods or tubes, uniformly distributed in parallel alignment in a continuous phase, with the axes perpendicular to the heat flow. The volume fraction of rods or tubes (the suspended phase) is v_s. The thermal conductivities of composite, matrix, and suspended phases are λ_c, λ_m and λ_s, respectively.

$$\lambda_c = \left[\frac{1}{\dfrac{1 - v_s^{1/2}}{\lambda_m} + \dfrac{1}{\dfrac{\lambda_m(1 - v_s^{1/2})}{v_s^{1/2}} + \lambda_s}} \right]$$

Appendix H

EXAMPLE OF CALCULATION OF THERMAL CONDUCTIVITY OF CONCRETE USING THE CUBIC MODEL

Data from ORNL-TM-2644, August, 1969, "Some Thermal Transport Properties of a Limestone Concrete", by J.P. Moore, R.S. Graves, J.G. Stradley, J.H. Hannah, and D.L. McElroy.

The purpose of this discussion is to provide an example of the use of the "Cubic Model" (see Fig. H.1) equation for calculating the thermal conductivity of a concrete of known composition and to compare calculated values with values from tests obtained by use of a radial heat flow apparatus. Proportions of ingredients used in the concrete are given in the ORNL reference. Physical and chemical properties of the limestone aggregate were obtained from the producers, Vulcan Materials Co., Hermitage, Tennessee. Weight percentages of initial constituents of the concrete were:

Portland cement, Type II	16.47%
Fine Limestone and Coarse Limestone	75.91%
Water	7.62%
Total	100.00%

The specific gravity of unhydrated cement in water was 3.2; that of the limestone was 2.71 (saturated, surface dry as used) and 2.695 (oven dry); the water absorption of the limestone was 0.57 percent. The limestone used in the concrete is predominantly calcitic with dolomitic and argillaceous constituents. Its chemical compound composition was:

$CaCO_3$	77.4 %
M_gCO_3	5.05%
SiO_2	11.61%
Al_2O_3	3.95%
Fe_2O_3	1.3 %

Acid Insoluble (14.2%)

The cement factor was estimated at 677 lb/yd^3 or 7.2 bags of cement per yd^3, a relatively "rich" mixture. The water-cement ratio was 0.46, by weight.

<u>Calculations</u>: In order to estimate the thermal conductivity of the

concrete by use of the Cubic Model equation, the following values are required: (1) thermal conductivity of the aggregate; (2) thermal conductivity of matrix (hardened cement paste); and (3) the fractional volume of the aggregate. The calculation of these values is presented in Table H.1 below. The first two rows list the weight and volume of the cement paste and aggregate. Next, the water content is calculated in rows 3 and 4. It was estimated that the chemically combined water was equal to 15 percent of the dry cement weight for seven days of curing in lime water, and 20 percent of the cement weight for 28 days of curing. It was further calculated that this combined water decreased in volume by 25 percent upon hydration and that this diminution in volume resulted in the take-up of a like volume of water during lime-water curing. The entrapped air content of oven-dry concrete (considered as part of the cement paste) was estimated at 1.0 percent by volume (row 5). This information allowed us to calculate the oven-dry and the saturated, surface-dry densities of the 7-day and 28-day cured concretes (rows 6 through 11). The moisture content, by weight, is then calculated in row 12. This is accomplished by dividing the saturated, surface-dry density (row 11) by the oven-dry density (row 9), and by subtracting 1.0 from the result. Row 13 shows the calculation of the fractional volume of the aggregate. Rows 16, 17 and 18 summarize the data required for the Cubic Model calculation. The thermal conductivity of the rock (row 17) was estimated based on its mineralogic composition and density.

Table H.2 presents the Cubic Model calculation. The thermal conductivity calculation is performed for oven-dry concrete (row 1) and the value obtained is then corrected for the moisture content at the time of testing (rows 2 and 3). Thermal conductivity moisture factors for limestone concretes have been proposed by Cammerer and Achtziger (1972). These factors range from 5.5 percent to 10 percent increase in thermal conductivity of the concrete for each one percent of moisture, by weight. The present study uses the pair of values of seven percent/one percent, which is given in the U.S.S.R. Standard SNiP II-3-79 (1986) for "stone concrete". Table H.3 summarizes the results.

TABLE H.1 CALCULATION OF THERMAL CONDUCTIVITIES OF AGGREGATE AND CEMENT PASTE FOR TWO LIMESTONE CONCRETES

Row no.		No. 120-6 (7d.)		No. 130.7 (28d.)	
		Weight	Volume Equivalent	Weight	Volume Equivalent
1.	Cement	16.47	5.15	16.47	5.15
2.	Limestone, fine and coarse	75.91	28.01	75.91	28.01
	Water:				
3.	Combined	2.47	1.85	3.29	2.47
4.	Evaporable	5.15	5.77	4.33	5.15
5.	Air (1% concrete volume)	-	0.41	-	0.41
6.	Add resorbed H_2O due to hydrate shrinkage	0.62	-	0.82	-
7.	Subtract aggregate absorbed H_2O	(0.43)	-	(0.43)	-
8.	Totals, oven-dry concrete	94.42	41.19	95.24	41.19
9.	Oven-dry density, (dry weight/vol.) x 62.4	143.2 pcf		144.3 pcf	
10.	Totals, saturated, cured	100.62	41.19	100.82	41.19
11.	Saturated, surface dry density, 62.4x (s.s.d. weight/vol.)	152.4 pcf		152.7 pcf	
12.	Moisture content, cured (by weight)	6.6%		5.8%	
13.	Volume fraction of limestone, V_s	28.01/41.19 = 0.68		28.01/41.19 = 0.68	
14.	Volume fraction of cement paste, V_m	1-0.68 = 0.32		1-0.68 = 0.32	

Row no.		No. 120-6 (7d.)		No. 130.7 (28d.)	
		Weight	Volume Equivalent	Weight	Volume Equivalent
15.	Density of cement paste, (Wt. paste/vol. paste) x 62.4	$\frac{16.47 + 2.47}{0.32 \times 41.19} = 89.7$ pcf		$\frac{16.47 + 3.29}{0.32 \times 41.19} = 93.55$ pcf	
16.	Thermal conductivity, dry paste, Btu/h-ft^2-(F/in.)*		2.85		3.03
17.	Thermal conductivity of limestone, (Btu/h-ft^2-(F/in.)		23.0		23.0
18.	Volume fraction of limestone, V_s		0.68		0.68

* Calculated from Equation: $\lambda = 0.166e^{0.3\sqrt{p}}$

TABLE H.2 CUBIC MODEL CALCULATIONS

Row no.		No. 120-6 (7d.)	No. 130-7 (28d.)
1.	Thermal conductivity concrete, oven-dry	11.1	11.4
2.	Moisture content	6.6% (9 d.)	5.8% (30 d.)
	Correction factor	1 + (0.066 x 7) = 1.46	1 + (0.058 x 7) = 1.41
3.	Calculated thermal conductivity concrete, with moisture Btu/h-ft^2-(F/in.)	1.46 x 11.1 = 16.2	1.41 x 11.4 = 16.1
4.	Test thermal conductivity concrete	15.0	15.7
	(Calc./test) - 1	+ 8.0%	+ 2.4%
5.	Density, air-dry, pcf	147.8	146.7
6.	Moisture content	3.2%	1.7%
	Correction factor	1 + (0.032 x 7) 1.22	1 + (0.017 x 7) 1.12
7.	Calculated thermal conductivity concrete	1.22 x 11.1 =	1.12 x 11.4 =
8.	Btu/h-ft^2-(F/in.)	13.6	12.8
	Test thermal conductivity concrete	13.4	14.4*
	Calc./test	+ 1.4%	- 11.4%

* Determined at elevated temperature upon partially sealed specimens.

TABLE H.3 SUMMARY OF THERMAL CONDUCTIVITY VALUES OBTAINED WITH CUBIC MODEL VS. TEST

	No. 120-6 (7d.)			No. 130.7 (28d.)		
	calc.	test	deviation	calc.	test	deviation
Thermal conductivity concrete saturated	16.2	15.0	+ 8.0%	16.0	15.7	+ 2.4%
Thermal conductivity concrete air-dry	13.6	13.4	+ 1.5%	-	-	-
Thermal conductivity concrete partially oven-dry	-	-	-	12.8	14.4	- 11.4

Mean deviation = 5.8% (signs neglected)
Mean bias + 0.1%

Discussion: While the virtually zero bias of calculations is fortuitous, the mean deviation of calculated versus test values for the limited number of tests considered here agrees very well with earlier calculations in this work.

The mean deviation of calculated concrete thermal conductivities from test values, for over 100 composite materials of various types was less than 6.0 percent, as shown in Figure 3.16 (Valore, 1987, International Masonry Institute report). The thermal conductivity moisture correction factor for limestone concrete was extracted from the estimates of Table 1.3. The thermal conductivity value for limestone is based on estimated mineralogical composition on the basis of chemical composition. A petrographic analysis would be preferred to show the proportion of SiO_2 present as quartz. An accurate thermal conductivity test value for the limestone would be even better.

There is some uncertainty in calculation for specimen 130-7, subjected to varying elevated temperatures for an extended period. This could transform the virtually amorphous, microcrystalline hydrated cement to a more highly crystalline material, increasing the thermal conductivity of the cement paste matrix. Also, while the thermal conductivity of limestone decreases at elevated temperature, that of hardened cement paste increases and these changes appear to cancel out, as shown in tests by Cammerer and Achtzinger (1972).

It may be noted that gravimetrically calculated densities for saturated concretes show excellent agreement with test values; this is to be expected.

APPENDIX I

MASONRY BLOCK SURVEY FORMS

The first survey forms (pages I.1 and I.2) was sent to concrete block manufacturers. The second survey form (page I.3) was sent to clay brick manufacturers.

I.2

CONCRETE BLOCK SURVEY

ASSESSMENT OF THERMAL AND PHYSICAL PROPERTIES OF MASONRY BLOCK PRODUCTS

Steven Winter Associates, Inc.

NCMA Region (circle one) 1 2 3 4 5

Manufacturer (optional)

Contact (optional)

1) Geographic Market Areas:
(Cities or Area Served)

2) Approximate no. of 8x8x16
equivalents shipped

	Light Weight (less than 105 pcf)	Medium Weight (105-125 pcf)	Normal Weight (over 125 pcf)	Total
3) Percentage shipped by weight category	%	%	%	100%

	12 in.	8 in.	6 in.	4 in.	Total
4) Percentage shipped by size (width)	%	%	%	%	100%

	12 in.	8 in.	6 in.	4 in.
5a) Percentage <u>solid block</u> by size	%	%	%	%
5b) Percentage of 2-core hollow block by size	%	%	%	%
5c) Percentage of 3-core hollow block by size	%	%	%	%
	100%	100%	100%	100%

I.3

CONCRETE BLOCK SURVEY

6) Please enclose descriptive literature on the blocks you manufacture most. Include dimensions if available.

7) Type of coarse aggregate used (If mineralogic composition is not available, please indicate quarry name and location)

		Normal Weight	Light Weight	
8)	Percent of coarse aggregate in two most prevalent mixes	%	%	Percentage indicated is by: volume _____ weight _____ (check one)
8b)	Percent of fine aggregate in two most prevalent mixes	%	%	
		100%	100%	
9)	Cement/aggregate ratio in two most prevalent mixes	1/	1/	Ratio indicated is by: volume _____ weight _____ (check one)
10)	Please indicate if you use insulating inserts	YES	NO	

11) If yes, please indicate type (optional)

12) Any comments or suggestions are welcome.

FORWARD TO: STEVEN WINTER ASSOCIATES, INC.
6100 EMPIRE STATE BUILDING
NEW YORK, NEW YORK 10001

I.4

CLAY BRICK SURVEY

ASSESSMENT OF THERMAL AND PHYSICAL PROPERTIES OF
MASONRY BLOCK PRODUCTS

Steven Winter Associates, Inc.

Manufacturer:

Contact:

		Area 1	Area 2	Area 3	Area 4	Area 5
1)	Geographic Shipping Areas: (for example Southern New Jersey: San Francisco/San Jose/ Sacramento/Santa Rosa; etc.					

		Area 1	Area 2	Area 3	Area 4	Area 5
2)	Approximate number of bricks shipped					

			Type 1	Type 2	Type 3	Type 4	Type 5	Type 6
3)	Brick Types Manufactured							
4)	Dimensions for each type	H	___	___	___	___	___	___
		W	___	___	___	___	___	___
		D	___	___	___	___	___	___

5) % Voids for each type

6) Core Size for each type

7) Panels & Frogs (comments)

8) Kiln-Fired density/weight:

9) Rate of Absorption:

10) Strength

11) Any additional information and/or brochures are welcome

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