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INSULATIVE LIGHTWEIGHT CONCRETE FOR BUILDING WALLS

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ABSTRACT: Research is currently being conducted to develop a portland cement concrete for use in low-rise building walls that will combine the structural, thermal insulating, and heat storage capacity functions of building walls. Concrete used as a structural material is generally in the unit weight range of 115 to 150 lb per cubic foot (1850 to 2400 kg/m^3). Such concretes while solving the structural and heat storage functions, have relatively low resistance to heat transfer.

A concrete weighing about 50 lb per cubic foot (800 kg/m^3), with a strength of 1000 to 1500 psi (6.9 to 10.3 MPa), and a thermal conductivity of about 1.5 Btu•in./hr•ft^2•°F (0.22 W/m•K) will meet the objectives of this study. This concrete can be used as a complete wall system in low-rise buildings and will eliminate many thermal bridges commonly associated with walls. Use of this concrete, without additional insulation, in an 8-in. thick wall of a low-rise building, will provide:

1. Sufficient strength
2. Adequate thermal resistance
3. Beneficial thermal storage properties

Total effect of these advantages is an economical cast-in-place concrete wall system with energy saving features.

INTRODUCTION AND BACKGROUND

Research is presently underway at Construction Technology Laboratories (CTL), a Division of the Portland Cement Association to develop more energy efficient building systems. The objective of this research program is to develop a portland cement concrete for use in low-rise building walls that will combine the structural, thermal insulating, and heat storage capacity function of exterior walls in one element. For many climates the concrete developed can be used as a complete wall system in low-rise buildings without the need of additional insulation.

The first phase of this program was a preliminary investigation to determine if laboratory research goals were obtainable. Work for the first phase was performed in response to an effort by Battelle Pacific Northwest Laboratory to identify and evaluate innovative concepts for conserving energy consumed in constructing buildings or

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during building use. The second phase was a feasibility study to identify building types and geographic locations where the lightweight concrete wall system can be used to advantage.

The remaining phases to be accomplished include characterization of the material, development of construction techniques, and laboratory tests of candidate concretes. This paper summarizes results of the first two phases. Work on the other phases has not been completed.

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

Generally, the lowest heat transmission is found in a wall with high thermal resistance and high storage capacity. Storage capacity is equal to the product of unit weight, specific heat, and wall thickness. However, thermal resistance of concrete decreases with increase in unit weight. Since heat transmission properties are more sensitive to changes in thermal resistance than to changes in unit weight or specific heat, the lightest concrete that has sufficient structural capacity will be used to satisfy this concept.

Concrete is available in a wide range of weights and strengths. Concretes weighing 50 pcf (800 kg/m^3) or less are called insulating concretes. Current technology limits the compressive strengths of these concretes to about 600 psi (4.1 MPa). Concretes in the 90 to 130 pcf (1440 to 2080 kg/m^3) range are known as structural lightweight aggregate concretes. These concretes have compressive strengths in the range of 2500 to over 9000 psi (17.2 to over 62.1 MPa), depending on materials, mix design and other factors. While these concretes have more than adequate strength for the proposed use, their thermal properties are inadequate.

A third category of lightweight concretes is in the weight range of 50 to about 90 pcf (800 to about 1440 kg/m^3). These are usually called fill concretes. Concretes in this weight range have not been widely used and their development has been somewhat neglected. The ultimate program objective is to develop concretes in the 45 to 55 pcf (720 to 800 kg/m^3) range with sufficient insulative properties and strength to meet the design requirements of exterior walls of low-rise buildings.

PHASE I - PRELIMINARY STUDY

The objective of Phase I, the preliminary study, was to develop a concrete having sufficient strength for use in low-rise building walls at the lowest possible unit weight, resulting in useful thermal storage and resistance properties.

Based on knowledge of previous research, the project objective, and what a limited research program might reasonably be expected to achieve, the goal of Phase I was set to develop a concrete having unit weight of under 65 pcf (1040 kg/m^3) and compressive strength of 1500 to 2000 psi (10.4 to 13.8 MPa). The ultimate program objective is to develop concretes in the 45 to 55 pcf (720 to 800 kg/m^3) range.

Results of laboratory research conducted for Phase I are published in Reference 19 and summarized in the following sections.

Eleven mixes were evaluated in the preliminary study. Measurements of thermal conductivity and specific heat were made using those concretes most successful in achieving the desired strength/weight properties. Other thermal properties were then determined analytically to evaluate overall thermal performance of the concrete.

Because of the tendency for lower density concretes to have high drying shrinkage, which influences cracking potential, measurements of drying shrinkage were included.

Materials

Most of the volume of concrete consists of aggregates. Thus unit weight of a concrete mix will depend to a great extent on the unit weight of aggregates selected and the amounts used in the mix. Compressive strength is dependent on water-cement ratio, concrete weight, aggregate properties, cement content, and slump. Therefore, mix design is a process that balances the above factors to result in concrete having the desired strength, weight, and thermal properties.

To obtain lightweight concretes having usable structural capacity, it is common to utilize expanded clay or shale structural lightweight aggregates. The use of most aggregates of this type will result in concretes with unit weights of 90 to 100 pcf (1440 to 1600 kg/m^3). Gravelite is a typical aggregate of this type. A few aggregates such as Livlite provide concrete weights as low as 80 pcf (1280 kg/m^3).

Since the fine sizes of these aggregates are denser than the coarse sizes, it is necessary to replace part or all of the fines with a less dense aggregate to obtain the lower concrete weights described in this program. Styropor, expanded polystyrene beads, and perlite, an expanded volcanic glass, were used for this purpose. These materials weigh 1.5 and 7 pcf (24 and 112 kg/m^3), respectively, as compared to about 40 to 60 pcf (640 to 960 kg/m^3) for expanded clay and shale fines.

Low unit weight concrete mix designs were prepared with these materials. Table 1 lists the cement and aggregate proportions, slump, air content, and fresh unit weight for the three mixes judged most promising of the 11 mixes made. Aggregate quantities are listed as cubic feet of dry loose material per cubic yard of concrete. Water was added to obtain a workable concrete with slump generally in the range of 2 to 5 in. (50 to 125 mm). An air entraining admixture was added to each mix and a water reducing agent to selected mixes to improve workability and durability.

Specimens were made from selected mixes for determination of compressive strength, drying shrinkage, specific heat, and thermal conductivity as described in the following sections.

Physical Properties

Compressive Strength

Specimens were made from most of the mixes for determination of compressive strength at 7 and 28 days. The specimens consisted of 4-in. (100-mm) diameter by 8-in. (200-mm) long cylinders. All cylinders were moist cured for 7 days, at which time three were tested in compression and the others were stored at 73°F (23°C) and 50% relative humidity (RH). At 28 days, three additional specimens were weighed and tested in compression. Table 2 shows unit weights and compressive strengths obtained on specimens from the three mixes judged most promising. These are Mix Nos. 7, 10, and 11. They offered the best combination of unit weight and strength obtained in Phase I.

TABLE 1 - CONCRETE MIX PROPORTIONS AND PROPERTIES

Mix No.	Description	Material Quantities per cu yd of concrete	Slump, in.	Air Content,%	Fresh Unit Weight, pcf
7	Cement	550 lb			
	Livlite coarse*	19 cu ft	2.1	2.3	63.8
	Livlite fine*	4 cu ft			
	Styropor	7 cu ft			
	Water Reducing Agent	**			
10	Cement	550 lb			
	Livlite coarse*	14 cu ft	4.0	4.3	68.8
	Livlite fine*	5 cu ft			
	Perlite	13 cu ft			
	Water Reducing Agent	**			
11	Cement	550 lb			
	Livlite coarse*	19 cu ft			
	Livlite fine*	4 cu ft	2.2	3.4	65.7
	Styropor	4 cu ft			
	Perlite	3 cu ft			

* Livlite aggregate gradation
Coarse - 1/8 in. to 5/8 in.
Fine - Passing 1/8 in.
**Water reducing agents added in quantities recommended by manufacturers.
Metric Equivalents:
1 lb = 0.453 kg
1 cu ft = 0.028 m^3
1 in. = 25.4 mm
1 pcf = 16.02 kg/m^3

TABLE 2 - CONCRETE UNIT WEIGHT, STRENGTH AND SHRINKAGE

Mix No.	Unit Weight, pcf		Compressive Strength, psi		Drying Shrinkage	
	Fresh	28 day*	7 day**	28 day*	%	Days of drying
7	63.8	60.8	1500	1990	0.127	535
10	68.8	62.7	1700	2110	0.156	521
11	65.7	62.1	1850	2440	0.125	521

*Moist-cured 7 days and then air-dried 21 days.
**Moist-cured 7 days.
Metric Equivalents:
1 pcf = 16.02 kg/m^3
1 psi = 0.007 MPa

Drying Shrinkage

Drying shrinkage is a property of concrete that contributes to cracking unless adequate provision is made in the design of a structure to accommodate the shrinkage. Since lower density concretes generally have higher drying shrinkage it was considered desirable to obtain shrinkage information on these concretes. Shrinkage specimens, 3x3x12-in. (75x75x300-mm) prisms, were cast with measuring pins embedded in their ends. After moist curing for 7 days, measurements using a vertical comparator were started, and continued as the specimens were drying at 70°F (21C) and 50% RH. Table 2 lists the data for specimens dried 521 to 535 days. As expected drying shrinkage of these concretes is considerably higher than that of normal weight concrete.

Thermal Properties

As mentioned previously, Mix Nos. 7, 10, and 11 offered the best combinations of unit weight and strength obtained in Phase I. Specific heat and thermal conductivity tests were performed on specimens from each of the three mixes.

Specific Heat

Specific heat is used to determine the storage capacity of building materials. Specific heat is defined as the ratio of the quantity of heat required to raise the temperature of a body one degree to that required to raise the temperature of an equal mass of water one degree.

Specific heats of concrete specimens were measured using a method similar to U.S. Army Corps of Engineers Specification CRD-C124-73, "Method of Test for Specific Heat of Aggregates, Concrete, and Other Materials (Method of Mixtures)."[6] Samples were selected from pulverized parts of two 3x6-in. (75x150-mm) cylinders cured one day in molds, and then at 73±3°F (23±1.7C) and 100% RH until test.

The method used determines the specific heat of saturated materials. To ensure complete saturation, a different procedure was used to saturate each of the three concrete types. Crushed samples from Mix No. 7, containing perlite, were immersed in room temperature water for 4 days prior to testing. Material from Mix No. 10, containing Styropor, was boiled in water for 6 hours and then immersed in room temperature water for an additional 2-1/2 days prior to testing. Material from Mix No. 11, containing perlite and Styropor, was oven-dried 20 hours and then vacuum saturated for 3 hours. The sample was then immersed in water for 22 hours.

To calculate specific heat of the material in a dry state, weights of the material in the particular dry state, and the saturated surface dry (SSD)* state must be known. Whiting, Litvin, and Goodwin[20] used the following equation to calculate specific heat of concrete for different moisture conditions:

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

where:

c = specific heat of samples at any moisture content

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

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

γ = SSD moisture content

$$\gamma = \frac{W_{SSD} - W_{OD}}{W_{SSD}} \qquad (2)$$

where:

W_{SSD} = SSD weight of sample

W_{OD} = ovendry weight of sample

After testing, specific heat samples were oven dried at 175°F (79C) so that SSD moisture contents could be determined.

Specific heat values obtained in this investigation are compared with previous perlite[16] and expanded shale[15] concrete test

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

results in Table 3. Values are for concrete in saturated surface dry, air dry, and ovendry conditions. Specific heat of concrete in the air dry and ovendry conditions were calculated using Eqs. (1) and (2). Specific heats of concrete in the saturated surface dry condition were measured.

Ovendry specific heats for the three mixes used in this investigation are similar. Air dry and saturated surface dry specific heats differ due to differences in moisture content. Since the specific heat of water is 1.0 Btu/lb•°F (4190 J/kg•K), the higher moisture content concretes have higher values of specific heat.

TABLE 3 - SPECIFIC HEAT OF LOW DENSITY CONCRETE

	Saturated Surface Dry			Air Dry			Ovendry	
Mix No.	Unit Weight, pcf	Moisture Content, % ovendry weight	Specific Heat, Btu/lb•°F	Unit Weight, pcf	Moisture Content, % ovendry weight	Specific Heat, Btu/lb•°F	Unit Weight, pcf	Specific Heat, Btu/lb•°F
Previous Perlite Concrete Test*(16)	68	62	0.444	46	9.5	0.179	42	0.100
7	70	24	0.316	61	7.1	0.208	57	0.152
10	80	39	0.390	63	9.2	0.224	57	0.152
11	84	46	0.423	62	8.1	0.220	57	0.158
Previous Expanded Shale Concrete Test**(15)	106	12	0.257	102	8.5	0.230	94	0.162

*Sample preparation included 18 hours of submersion in water and 6-1/2 hours of boiling.
**Samples submerged in water for 5 days prior to testing.
Metric Equivalents:
1 pcf = 16.02 kg/m^3
1 Btu/lb•°F = 4186.8 J/kg•K

Thermal Conductivity

The hot wire method was used to determine apparent thermal conductivity of air dried prisms. Concrete prisms from Mix Nos. 7, 10, and 11 were cast with a nickel-chromium constantan thermocouple embedded along their central longitudinal axis. Test specimens measured 4x4x8 in. (100x100x200 mm).

Thermal conductivity values obtained using the hot wire method[8] are given in Table 4. Values for previous tests on perlite[16] and expanded shale[15] concretes are also listed in Table 4.

Care must be taken when comparing thermal conductivity test results from different test methods. The hot wire method generally gives higher test results than the conventional guarded hot plate test method (ASTM Designation: C177). However, the guarded hot plate method with embedded thermocouples yields higher results than the hot wire test method.[14] A comparison of thermal conductivity test methods and results may be found in References 14 and 18.

Figure 1 illustrates that thermal conductivity of these concretes increases as unit weight increases. This relationship has been documented by numerous investigators.[14]

Thermal conductivity of a given concrete increases with moisture content. Specimens allowed to air dry for a longer period have lower conductivity values.

TABLE 4 - RESULTS FROM HOT WIRE THERMAL CONDUCTIVITY TESTS ON AIR DRY SPECIMENS

Mix No.	Air Dry Unit Weight, pcf	Air Dry Moisture Content, % ovendry weight	Measured Thermal Conductivity, $\frac{Btu \cdot in.}{hr \cdot ft^2 \cdot °F}$
Previous Perlite Concrete Test(16)	50*	9.5	1.9***
7	61**	7.1	2.4
10	63**	9.2	3.1
11	62**	8.1	3.1
Previous Expanded Shale Concrete Test(15)	101*	8.5	6.7***
Previous Normal Weight Concrete Test(17)	144*	2.1	18.9***

*Air dry unit weight of hot wire test specimen at designated moisture content.
**Air dry unit weight determined from 4x8-in. (100x200-mm) compression test cylinders.
***Interpolated from measured results at other moisture contents.
Metric Equivalents:
1 pcf = 16.02 kg/m^3
1 Btu·in./hr·ft^2·°F = 0.144 W/m·K

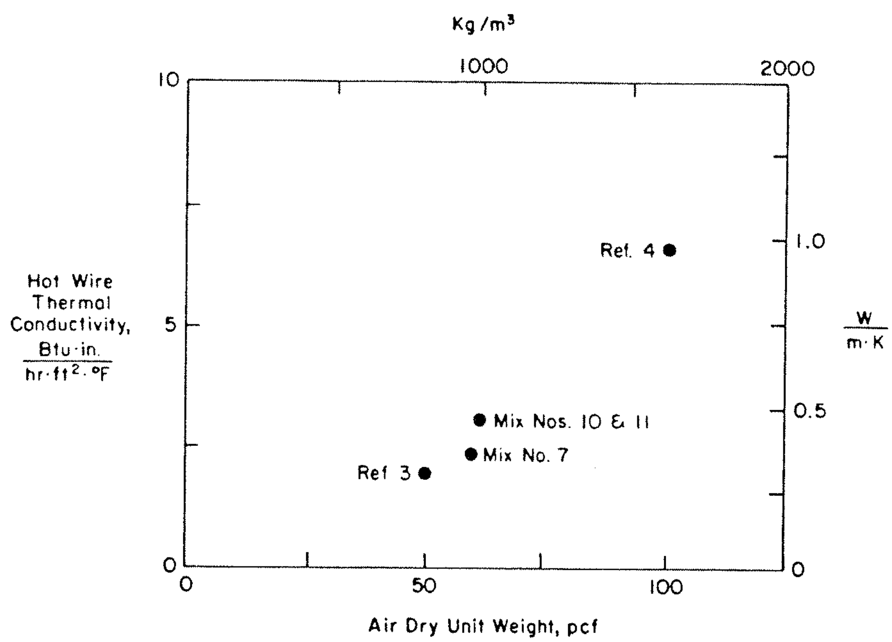


Fig. 1. Results from Hot Wire Thermal Conductivity Tests on Air Dry Specimens

Prediction of other Thermal Properties

Thermal diffusivity was calculated from measured values of thermal conductivity, specific heat, and unit weight. Other dynamic thermal properties were estimated from diffusivity and previous calibrated hot box test results.

Thermal Diffusivity

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

Theoretically, thermal diffusivity can be calculated from the following equation:

$$\alpha = \frac{k}{\rho \cdot c} \quad (3)$$

where:

α = thermal diffusivity, ft^2/hr (m^2/s)
k = thermal conductivity, Btu/hr•ft•°F (W/m•K)
ρ = unit weight, pcf (kg/m^3)
c = specific heat, Btu/lb•°F (J/kg•K)

Properties used in Eq. (3) should be obtained at the same moisture content.

Values of thermal diffusivity calculated for concrete Mix Nos. 7, 10, and 11 are given in Table 5. Values calculated from previous perlite[16] and expanded shale[15] concrete test results are also shown in Table 5.

TABLE 5 - CALCULATED THERMAL DIFFUSIVITY

Mix No.	Air Dry Unit Weight, pcf	Air Dry Specific Heat, Btu/lb•°F	Air Dry Thermal Conductivity, $\frac{Btu \cdot in.}{hr \cdot ft^2 \cdot °F}$	Air Dry Moisture Content, % ovendry weight	Calculated Air Dry Thermal Diffusivity, ft^2/hr
Previous Perlite Concrete Test[16]	46*	0.179	1.9	9.5	0.019
7	61**	0.208	2.4	7.1	0.016
10	63**	0.224	3.1	9.2	0.018
11	62**	0.220	3.1	8.1	0.019
Previous Expanded Shale Test[15]	102*	0.230	6.7	8.5	0.024

*Air dry unit weight of calibrated hot box test specimen.
**Air dry unit weight of compression test cylinders.
Metric Equivalents:
1 pcf = 16.02 kg/m^3
1 Btu/lb•°F = 4186.8 J/kg•K
1 Btu•in./hr•ft^2•°F = 0.144 W/m•K
1 ft^2/hr = 25.8 mm^2/s

Thermal Lag and Reduction in Amplitude

Dynamic calibrated hot box tests of wall assemblies may be used to determine dynamic properties of thermal lag and reduction in amplitude. These properties were not measured as a part of this study, but were estimated using results from calibrated hot box tests on perlite[16] and expanded shale[15] concrete walls.

Calibrated hot box tests (ASTM Designation: C976[3]) provide data on heat transmission characteristics of full-size wall assemblies under steady-state and dynamic temperature conditions. Dynamic tests provide data on dynamic thermal response under controlled conditions that simulate actual temperature changes in building envelopes. Dynamic response includes heat storage capacity as well as heat transmission characteristics of the wall assembly.

The facility was designed to accommodate walls with thermal resistance values ranging between 1.5 to 20 $hr \cdot ft^2 \cdot °F/Btu$ (0.26 to 3.52 $K \cdot {}^2/W$). Nominal overall dimensions of test assemblies are 103x103 in. (2.62x2.62m). The test specimen is placed between an outdoor chamber and indoor chamber. The outdoor chamber can be held at a constant temperature or cycled between -15°F and 130°F (-26 and 54°C). Temperature cycles can be programmed to obtain the desired time-versus-temperature relationship. The indoor chamber simulates an indoor environment and can be maintained at constant room temperatures between 65°F and 80°F (18 and 27°C).

One series of tests performed in the calibrated hot box was a dynamic thermal study on three concrete wall sections.(18) One was a normal weight wall weighing 144 pcf (2310 kg/m^3), one a structural lightweight wall weighing 102 pcf (1630 kg/m^3), and the third a low density wall weighing 46 pcf (740 kg/m^3). Results of these tests are given in separate reports(15,16,17) and summarized in a paper presented at the ASHRAE/DOE Conference in 1982.(18) These low density and structural lightweight concrete walls were made from the same concrete as the specimens used to determine "previous" perlite and expanded shale, respectively, concrete test results listed in Tables 3, 4, and 5.

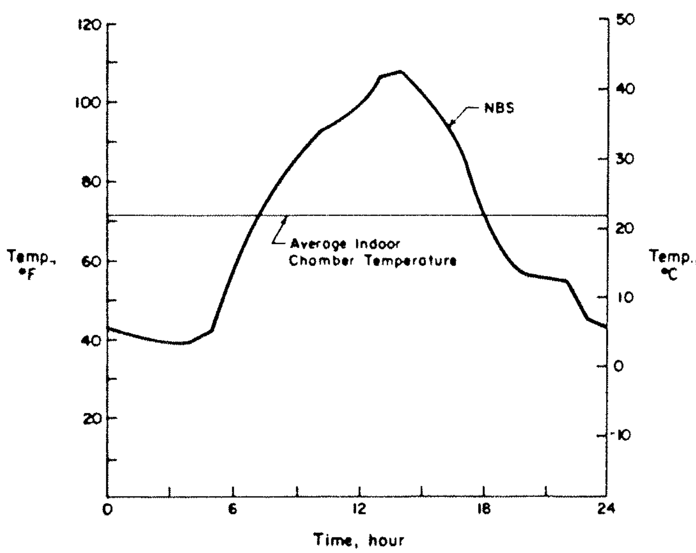


Fig. 2. Outdoor Chamber Air Temperature for NBS Dynamic Test Cycle

Three diurnal test cycles were performed on the low density and structural lightweight concrete walls. One test cycle, denoted the NBS temperature cycle, was used to analyze data in Phase I. The NBS cycle, illustrated in Figure 2, results in an outdoor air temperature that fluctuates above and below the indoor air temperature. This causes reversal of heat flow within the wall during the 24-hour cycle.

Two coefficients determined from dynamic calibrated hot box test results are thermal lag and reduction in amplitude of peak heat flow. These coefficients are illustrated in Fig. 3.

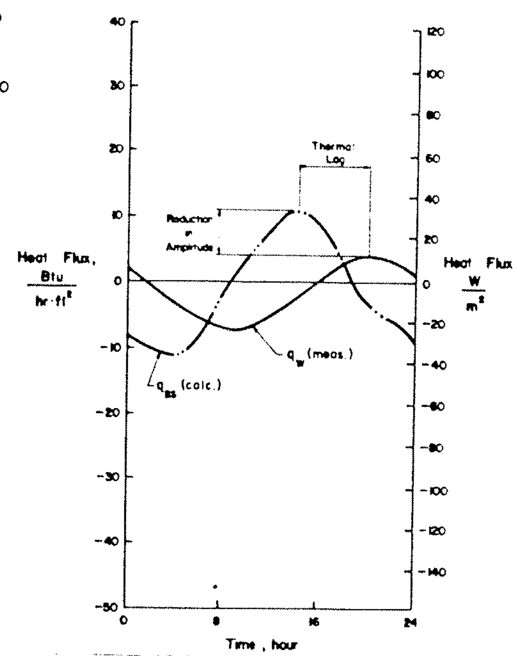


Fig. 3. Definition of Thermal Lag and Reduction in Amplitude

Thermal lag is the time required for the maximum or minimum indoor surface temperature to be reached after the maximum or minimum, respectively, outdoor air temperature is attained. Lag may also be defined as the time required for the maximum or minimum heat flow rate, q_w, to be reached after the maximum or minimum heat flow rate based on steady-state prediction, q_{ss}, is attained. The steady-state prediction is determined from wall conductance and surface temperatures. Thermal lag is indicative of both thermal resistance and heat storage capacity, since both of these factors influence the rate of heat flow.(16)

Percent reduction in amplitude is defined as the percent reduction in measured peak heat flow when compared to peak heat flow calculated using steady-state theory. Percent reduction in amplitude varies depending on the temperature cycle applied to a given wall.

Under certain dynamic temperature conditions, the combination of thermal conductivity and unit weight of low density concrete walls provides reduction and delay in peak heat flows that can result in significant energy savings. Lower peak heat flows may result in lower total energy costs for maintaining constant indoor air temperatures. Calibrated hot box tests may be used to determine energy requirements for a particular temperature cycle. Delay in peak heat flow, or thermal lag, is beneficial because the delay makes feasible the use of other inexpensive systems such as ventilation to aid in maintaining constant indoor air temperature. If the building envelope can be effectively used to delay the occurrence of peak loads, it may be possible to improve overall energy efficiency. The lag effect is also useful for passive solar applications.

Thermal lag and reduction in amplitude are dependent on the following:(5)

$$[(L^2/\alpha)/P]^{1/2} = \frac{(R)\cdot(\rho c L)^{1/2}}{P} \tag{4}$$

where:

- L = wall thickness, ft (m)
- α = thermal diffusivity, ft^2/hr (m^2/hr)
- P = time period required to complete a single cycle, hr
- ρ = wall density, pcf (kg/m^3)
- c = wall specific heat, Btu/lb•°F (J/kg•K)
- R = wall resistance, hr•ft^2•°F/Btu (m^2•K/W)

Thermal lag and reduction in amplitude are dependent on storage capacity ($\rho c l$) and thermal resistance (R).

Thermal lag and reduction in amplitude of heat flow rates in concretes for this study may be <u>estimated</u> using the parameter presented and previous calibrated hot box test results. For purposes of this paper, time period, P, is a constant equal to 24 hours. Therefore, variations in lag and reduction in amplitude are dependent on $(L^2/\alpha).^{1/2}$

Table 6 lists values of wall thickness, diffusivity, and $(L^2/\alpha)^{1/2}$ for the three concretes in this study, the previous perlite concrete test, and the previous expanded shale concrete test. Thermal lag and reduction in amplitude for concrete from Mix Nos. 7, 10, and 11 are interpolated or extrapolated from previous test results using the assumption that the parameters are linearly dependent on $(L^2/\alpha).^{1/2}$

Results in Table 6 show that concrete from Mix Nos. 10, and 11 would perform approximately the same as the previous perlite concrete.

TABLE 6 - THERMAL LAG AND REDUCTION IN AMPLITUDE

Mix No.	L Wall Thickness, ft	α Thermal Diffusivity ft^2/hr	$(L^2/\alpha)^{1/2}$, $(hr)^{1/2}$	NBS Test Cycle: Average Thermal Lag, hrs	NBS Test Cycle: Reduction in Amplitude, %
Previous Perlite Concrete Test[16]	0.71*	0.019	5.2	8.5	61*
7	0.70**	0.016	5.5	10⁺	60⁺
10	0.70**	0.018	5.2	9⁺	60⁺
11	0.70**	0.019	5.1	8⁺	60⁺
Previous Expanded Shale Test[15]	0.69*	0.024	4.5	5.5	54*

*Measured
**Assumed
⁺Estimated by extrapolation
Metric Equivalents:
1 ft = 0.305 m
1 ft^2/hr = 0.093 m^2/hr

Mix No. 7 has the most beneficial properties: high thermal lag and reduction in amplitude values. For the three mixes in this study, thermal lag varies from 8 to 10 hours and percent reduction in amplitude values are approximately 60%.

Care must be taken in using extrapolated values. Dynamic calibrated hot box tests must be performed to verify thermal lag and percent reduction in amplitude. Also, note that reduction in amplitude values are valid only for the NBS test cycle. Other test cycles will give different values for reduction in amplitude.

PHASE 2 - FEASIBILITY STUDY

Based on the results of the preliminary study, it is believed that a concrete weighing about 50 pcf (800 kg/m^3), having a compressive strength of 1000 to 1500 psi (6.9 to 10.3 MPa), and a thermal conductivity of about 1.5 Btu•in./hr•ft^2•°F (0.22 W/m•K) can be developed. A feasibility study was performed to determine building types and geographic locations where this lightweight concrete can be used for exterior walls.[7] An 8-in. (200-mm) thick concrete exterior wall was assumed in the analysis.

A computer analysis was performed to determine annual heating and cooling loads for two buildings with the proposed lightweight concrete wall system. The two buildings selected were a one-story commercial building and a three-story apartment building. These buildings were each analyzed for six cities in the United States. Results are compared to previous investigations[4,11] of the same buildings with different wall constructions.

The analysis was carried out using the Building Loads Analysis and System Thermodynamics (BLAST)[12] computer program. This program determines annual heating and cooling loads based on an hour-by-hour analysis for a full year. Climatic data were obtained from Test Reference Year[10] weather tapes. For this investigation, only the loads portion of the BLAST program was used.

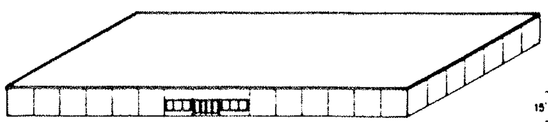
Building Descriptions

Commercial Building

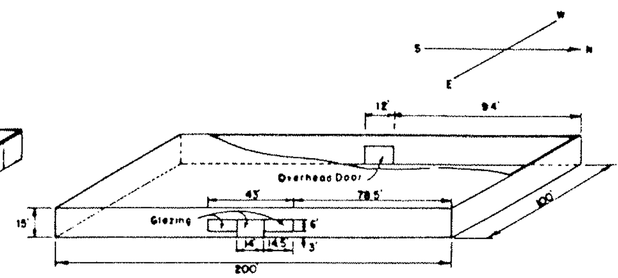
The commercial building analyzed in this investigation is illustrated in Fig. 4. The one-story building had slab-on-grade construction with 20,000 sq ft (1900 m^2) of floor area. Building height was 15 ft (4.6 m). Windows and door glazing comprised approximately 10% of the surface area of the east wall.

The building had a flat roof that was insulated to satisfy the requirements of ASHRAE Standard 90A-1980.(1)

Performance of the building using the lightweight concrete wall system was compared to the performance of a similar building using a metal wall system. The metal wall system analyzed was typical of that found in metal buildings. Metal walls with different levels of insulation were analyzed using the BLAST computer program. Wall R-values ranged from approximately 2 to 20 hr•ft^2°F/Btu (0.4 to 3.5 m^2•K/W).



(a) Building Isometric.

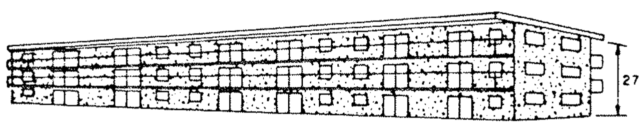


(b) Building Geometry

Fig. 4 Commercial Building Isometric

Residential Building

The low-rise multi-family residential building analyzed in this investigation is illustrated in Fig. 5. This three-story apartment building had 18,000 sq ft (1700 m^2) total floor area. Windows on the north and south walls comprised about 10% of the area of these walls. Sliding glass doors and windows on the east and west walls totaled approximately 26% of the area of these walls. Shading was provided on the east and west sides by 6-ft (2-m) balconies for the lower floors and 6-ft (2-m) overhangs for the top floor. No shading was provided



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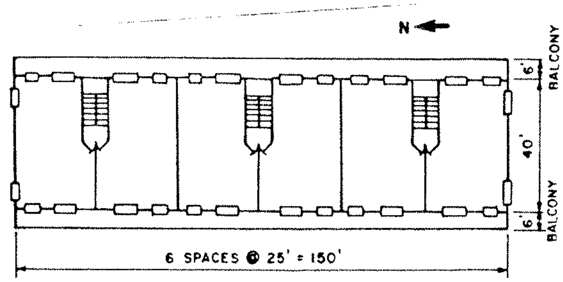


(b) Typical Floor Plan

Fig. 5 Residential Building Isometric

on the north and south walls. Double glazing was used in all windows and doors.

The building using the 8-in. (200-mm) thick lightweight concrete had an insulated precast concrete hollow core slab roof. Intermediate floors were also precast concrete hollow core slabs. The performance of this building was compared to that of an all wood frame building.

The level of insulation in the roof of both buildings analyzed was that required by HUD Minimum Property Standards for Multi-Family Housing (HUD-MPS)[13] for each location. Wood frame walls with different levels of insulation were analyzed using the BLAST computer program. Wall R-values ranged from approximately 5 to 21 hr•ft^2•°F/Btu (0.9 to 3.7 m^2•K/W).

Results of Blast Analysis

In this feasibility study, the BLAST computer analysis was performed on the commercial and residential buildings previously described.

Commercial Building

Table 7 shows annual heating load, annual cooling load, and annual total load for the one-story commercial building for the six cities indicated. Annual loads are results from the BLAST computer analysis assuming exterior walls are constructed using lightweight concrete. Heating degree day and cooling degree day values are based on 65°F (18°C) and were obtained from the ASHRAE Handbook of Fundamentals.[2]

TABLE 7 - ANNUAL LOADS FOR COMMERCIAL BUILDING[7]

Location	Heating Degree Days,[2] °F-days	Cooling Degree Days,[2] °F-days	Annual Heating Load, BtuX10^6	Annual Cooling Load, BtuX10^6	Annual Total Load, BtuX10^6
Chicago	6155	713	336.0	199.1	535.1
Seattle	5145	134	215.1	99.4	314.5
Wash., D.C.	4224	1491	181.2	289.7	470.9
Atlanta	2961	1469	65.5	406.5	472.3
Phoenix	1765	3334	17.0	687.8	704.8
Tampa	683	3152	2.1	731.5	733.6

Metric Equivalents:
°F-days = 0.556 °C-days
BtuX10^6 = 0.293 MW•hr

Residential Building

Table 8 shows annual heating load, annual cooling load, and annual total load for the three-story apartment building for the six cities indicated. Annual loads are results from the BLAST computer analysis assuming exterior walls are constructed using lightweight concrete. Cooling degree day values are based on 65°F (18°C) and were obtained from the ASHRAE Handbook of Fundamentals.[2] Heating degree day values are based on 65°F (18°C) and were obtained from Reference 9.

Comparisons

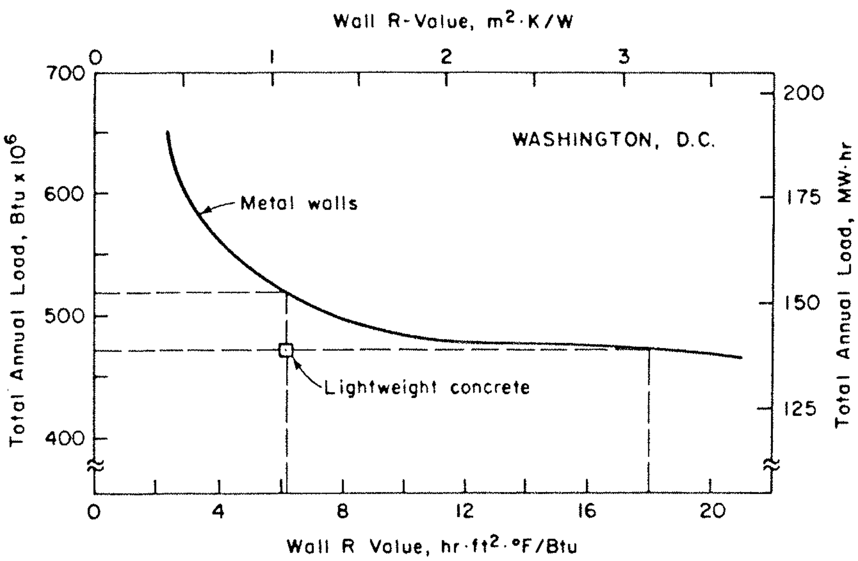
Previous investigations[4,11] indicate that thermal mass in a building affects total annual load. The total annual load of the commercial building using the lightweight concrete walls was compared to

TABLE 8 - ANNUAL LOADS FOR RESIDENTIAL BUILDING(7)

Location	Heating Degree Days,(9) °F-days	Cooling Degree Days,(2) °F-days	Annual Heating Load, $Btu \times 10^6$	Annual Cooling Load, $Btu \times 10^6$	Annual Total Load, $Btu \times 10^6$
Chicago	6640	713	313.3	206.4	519.7
Seattle	5190	134	215.2	104.2	319.4
Wash., D.C.	4240	1491	153.5	317.3	470.8
Atlanta	2990	1469	72.5	350.2	422.7
Phoenix	1680	3334	6.3	671.6	677.9
Tampa	700	3152	0.3	651.1	651.4

Metric Equivalents:
°F-days = 0.556 °C-days
$Btu \times 10^6$ = 0.293 MW·hr

the total annual load of the commercial building using metal walls reported in Reference 4. To compare the two wall systems, an equivalent R-value was determined for the lightweight concrete walls. The equivalent R-value indicates the level of metal wall insulation necessary to provide the same total annual load as the lightweight concrete wall system. The method of computing the equivalent R-value is shown in Fig. 6 for the commercial building in Washington, D.C.



COMMERCIAL BUILDING: WASHINGTON, D.C.

Fig. 6 Total Annual Load vs. Wall R-Value

Lightweight concrete residential building was compared in a similar manner to a wood frame residential building reported in Reference 11. Equivalent R-values for the lightweight concrete walls for both the commercial and residential buildings are shown in Table 9. R-value of the lightweight concrete wall system was 6.18 hr•ft^2•°F/Btu (1.09 m^2•K/W). Equivalent R-values shown in Table 9 are all greater than this. Equivalent R-values which are greater than the actual R-value indicate the effect of thermal mass of the lightweight concrete wall system.

TABLE 9 - EQUIVALENT R-VALUES

Location	Commercial Building		Residential Building	
	Total Annual Load, Lt. Wt. Concrete Walls, BtuX10^6	Equivalent R-Value, Metal Walls, hr•ft^2•°F/Btu	Total Annual Load, Lt. Wt. Concrete Walls, BtuX10^6	Equivalent R-Value, Wood-frame Walls, hr•ft^2•°F/Btu
Atlanta	472.3	*	422.7	*
Chicago	535.1	10.3	519.7	7.1
Phoenix	704.8	*	677.9	--
Seattle	314.5	--	319.4	8.0
Tampa	733.6	*	651.4	*
Wash., D.C.	470.9	18.0	470.8	7.7

*Equivalent R-Value cannot be determined. Lightweight concrete wall system had an equivalent R-Value greater than 20 hr•ft^2•°F/Btu.

Note: Wall R-Value of lightweight concrete wall system is 6.18 hr•ft^2•°F/Btu.

Metric Equivalents:
BtuX10^6 = 0.293 MW•hr
hr•ft^2•°F/Btu = 0.18 m^2•K/W

SUMMARY

A research program was initiated at Construction Technology Laboratories to develop an energy-conserving portland cement concrete for use in low-rise building walls. This concrete will combine the structural, thermal insulating, and heat storage functions of exterior walls in one element. The ultimate objective of research is to develop a lightweight concrete with a unit weight of 45 to 50 pcf (720 to 800 kg/m^3), compressive strength of 1000 to 1500 psi (6.9 to 10.3 MPa), and thermal conductivity of approximately 1.5 Btu•in./hr•ft^2•°F (0.22 W/m•K).

Two phases of research have been completed. During Phase 1 preliminary laboratory research was conducted to obtain concretes having air dry unit weights less than 65 pcf (1040 kg/m^3) and compressive strengths in the range of 2000 psi (13.8 MPa). Desirable mixes contained expanded clay and shale coarse aggregates with expanded polystyrene beads and perlite fine aggregates. Unit weight, compressive strength, drying shrinkage, specific heat, and thermal conductivity were measured on concrete specimens. Dynamic thermal properties of thermal diffusivity, lag, and reduction in peak heat flow were estimated from measured properties. Results indicate the lightweight concrete has desirable thermal storage properties.

Phase 2 was a feasibility study to identify building types and geographic locations where the lightweight concrete wall system can be used. A one-story commercial building and a three-story residential building were modeled using the BLAST computer program. Exterior walls were assumed to be 8-in. (200-mm) thick, lightweight concrete with a thermal conductivity of 1.5 Btu•in./hr•ft^2•°F (0.22 W/m•K). Results were compared to previous studies of the same commercial building with metal walls, and the same residential building with wood frame walls. Comparisons verify the lightweight concrete has acceptable thermal performance for use as exterior walls in commercial and residential buildings.

Results from Phases I and II indicate program objectives are obtainable.

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Mr. J. S. Balik, Building Design Engineer, Building Design and Construction Department, Portland Cement Association, determined annual loads using the BLAST computer program. Mr. S. C. Larson, Assistant Construction Engineer, analyzed BLAST results for the feasibility study.

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