S1-9-2

OPTIMAL THERMAL MASS AND R-VALUE IN CONCRETE

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ABSTRACT:

The thermal performance of wall systems is determined by two parameters. The steady-state thermal resistance is well established in building codes. Thermal inertia, the reluctance of the wall to change temperature when exposed to a dynamic temperature regime, is considerably more complicated, less well understood and has been approximated in codes and standards by crude assumptions. This paper reports the influence of density, thermal conductivity, and specific heat on the dynamic testing of wall and unit specimens and the impact of these criteria on energy transfer. Results show that for exterior single-layer uninsulated concrete product walls, the beneficial effects of thermal inertia (sometimes referred to as thermal mass) are increased as density is reduced from 2400 kg/m³ (150 lb/ft³) to 800 kg/m³ (50 lb/ft³).

Keywords: concrete, concrete masonry, density, lightweight concrete, specific heat, thermal conductivity, thermal damping, thermal diffusivity, thermal inertia, thermal lag, thermal mass, thermal resistance.

1. INTRODUCTION

The thermal performance of wall systems is described by two parameters:
(a.) Thermal resistance: the walls resistance to a steady-state heat flow. This is well established and commonly referred to in building codes and product literature as the R-value of the wall or as R-values of individual wall components. The reciprocal of thermal resistance is thermal conductance, and for a homogenous material of unit thickness, thermal conductivity.
(b.) Thermal inertia (i.e., thermal mass): Relates to the reluctance of the wall to change temperature when exposed to variable temperatures such as daily fluctuations of the outdoor air. Thermal inertia depends on thermal diffusivity, which is a function of thermal conductivity, specific heat, and density.

Generally, standard practice considered only the thermal resistance parameter because of the simplicity and relative accuracy of the calculation of steady-state heat flow for “light frame” construction. Steady-state heat flow (which does not include thermal inertia) can be used to predict the thermal performance of wood and steel frame construction fairly accurately, but significantly underestimates the thermal performance and energy efficiency mass walls such as those constructed of masonry or concrete. While the performance of substantial wall systems (such as masonry, concrete, adobe, and wood logs) has been intuitively understood and widely recognized for many centuries, the procedure for defining the beneficial behavior of thermal inertia remains complex to calculate and present in simple form for building codes.

The density of concrete is primarily related to the type and density of the incorporated aggregate. Sand and gravel or crushed stone are the most common aggregates in normal weight concrete, where the typical density is in the range of 2080 to 2400 kg/m³ (130 to 150 lb/ft³). Many lightweight aggregates from expanded shale, clay or slate to pumice are used for lighter weight concretes with densities of 1120 to 2080 kg/m³ (70 to 130 lb/ft³). Also, admixtures can be used to entrap air in the concrete, which is another method of reducing concrete density.

The *International Energy Conservation Code* (*IECC*) [1] and *ASHRAE 90.1* [2] provide simple approximations that reflect the influence of the thermal/physical properties of concrete that are used in the determination of energy loss through building walls. This paper provides an analytical method for determining optimum properties of ready-mixed concrete as well as the concrete used in the manufacture of concrete masonry units (CMU). Also reported on are modifications to specimen preparation that allow the determination of the thermal diffusivity for zero slump (high void) of fresh concrete obtained at the manufacturing facility. Thermal values obtained from these testing procedures support the approximations in the *IECC* and *ASHRAE 90.1* used to qualify mass walls for benefits obtained from thermal inertia.

2. THERMAL CONDUCTIVITY

Thermal conductivity is the rate at which heat flows through a material for a unit temperature difference and unit area, and is used to determine a materials steady-state heat flow. Thermal conductivities of all types of concrete and masonry materials are documented in the *ACI 122R-02 Guide to Thermal Properties of Concrete and Masonry Systems* [3], which provides data showing that lower thermal conductivity (higher R-value) is generally achieved with lower density materials. Thermal conductivity of concretes of differing densities as measured by various methodologies was also reported in the paper "*Calibrated Hot Box Tests of Thermal Performance of Concrete Walls*" [4].

In a series of comprehensive papers, VanGeem et. al. reported the thermal conductivities measured on small specimens (guarded hot plate ASTM C 177 and hot wire) as well as results developed in a Calibrated Hot Box (ASTM C 976) under steady-state conditions on full sized walls (2.6 m x 2.6 m (8.6 ft x 8.6 ft)) [5, 6, 7]. Theses results are shown in Table 1.

A formula proposed by Valore [8] provides an approximation for the thermal conductivity of moist concrete:

$$k = 0.0865 \cdot e^{0.00125D} \qquad \text{(SI)} \qquad (1)$$

where,

k = thermal conductivity, W/m·K
D = density, kg/m³

$$k = 0.6e^{0.02D} \qquad \text{(IP)}$$

where,

k = thermal conductivity, Btu·in./h·ft²·ºF
D = density, lb/ft³

It's important to note that Valore's formula is applicable only to lightweight concretes with densities less than 1600 kg/m³ (100 lb/ft³). Thermal conductivity of concretes containing normal weight aggregates with densities above 1600 kg/m³ (100 lb/ft³) cannot be accurately estimated as a function of density because of the wide range of mineralogy that directly effect the thermal conductivity of natural aggregates giving them a large distribution range.

3. SPECIFIC HEAT

Specific heat is the ratio of the amount of heat required to raise the mass of a material one degree to the amount of heat required to raise the same weight of water one degree. Harmathy and Allen reported that for all practical purposes the specific heat of lightweight aggregate concrete is similar to that of normalweight concrete [9]. The ACI 122 guide [3] recommends specific heat values of 880 to 920 J/kg·K (0.21 to 0.22 Btu//lb·ºF) over a concrete density range of 1280 to 2240 kg/m³ (80 to 140 lb/ft³).

4. THERMAL DIFFUSIVITY

Thermal diffusivity is a measure of how quickly a material changes temperature, and can be either calculated or measured. It is calculated by:

$$\alpha = k/Dc \qquad (2)$$

where,

α = thermal diffusivity, m²/s (ft²/h)
D = density, kg/m³, (lb/ft³)
c = specific heat, J/kg·K (Btu/lb·ºF)
k = thermal conductivity, W/m·K (Btu·ft/h·ft²·ºF)

High thermal diffusivity indicates that temperature change through a material will be fast. Wall materials such as concrete and masonry have low thermal diffusivity and respond slowly to an imposed temperature.

Thermal diffusivity is measured by the United States Army Corps of Engineers (USACE) "*Method of Test for Thermal Diffusivity of Concrete*" CRD – C 36 [10]. Typically, thermal diffusivity is determined by measuring the temperature differentials between the interior and surface of a heated 150 x 300-mm (6 x 12-in.) concrete cylinder as it cools in a constant temperature bath of running water.

Table 2 lists the results of diffusivity tests conducted in commercial testing laboratories in accordance with USACE CRD-C 36 on cast-in-place concretes and zero slump CMU concrete of different constituents and densities. Mixtures of CMU concrete were obtained from CMU plant mixers during production of commercial CMUs. The mixtures were rodded in three layers in a standard 150 x 300-mm (6 x 12-in.) cylinder mold with 25 blows/layer using a tamping rod in accordance with ASTM C 192 "*Standard Practice for Making and Curing Test Specimens in the Laboratory"*. Care was taken to locate the thermocouple in the center of the cylinder.

Using Eq. 1 and the density of the CMU, the calculated thermal conductivity of CMU concrete Specimen S5 from Table 2 would yield $k_{S5} = 0.0865 \cdot e^{0.00125 \cdot (1440)} = 0.52$ W/m·K ($k_{S5} = 0.6e^{0.02 \cdot (90)} = 3.6$ Btu· in./h·ft²·°F). Using Eq. 2, the calculated thermal conductivity, and a specific heat of 880 J/kg·K (0.21 Btu/lb·°F), the resulting calculated thermal diffusivity is:
(SI) $\alpha_{s5} = (0.52)/(880 \cdot 1440) = 4.1 \times 10^{-7}$ m²/s
(IP) $\alpha_{s5} = (3.6/12)/(0.21 \cdot 90) = 0.016$ ft²/h
The calculated result is the same as the test result provided in Table 2.

5. THERMAL LAG

Thermal lag is a measure of the response of the inside surface temperature to fluctuations in outdoor temperature. Lag is sensitive to both thermal resistance and thermal inertia properties of the wall. Calibrated hot box test results [5, 6 and 7] provide comprehensive data on tests on full scale, single layer ready-mixed concrete walls of differing densities under steady-state and dynamic temperature conditions. These tests determined:
(a.) Thermal lag: a measure of the response of inside surface temperature and heat flow through a wall to fluctuations in outdoor temperature.
(b.) Reduction in amplitude: The damping effect on peak heat flow.
(c.) Reduction in measured energy: The energy necessary to maintain a constant indoor temperature while outdoor temperature is varied compared to steady-state predictions.

It can be seen from Table 3 that as the wall's concrete density was reduced from 2290 to 1590 to 900 kg/m³ (143 to 99 to 56 lb/ft³):

- Average thermal lag increased from 4 to 5.5 to 8.5 hours;
- Amplitude reduction increased from 45 to 54 to 63%;
- The ratio of total energy decreased from 66 to 60 to 53%.

It should be noted that these results are only comparative and were developed on the basis of the wide temperature swing used in the NBS-10 test cycle (a simulated sol-air cycle used by the National Bureau of Standards, now the National Institute of Standards and Technology) in which mean outdoor temperature of the cycle was approximately equal to the mean indoor temperature [4]. Figure 1 [11] depicts the thermal lag and reduction in amplitude (damping) on a normalweight concrete wall in a moderate climate.

Thermal lag increases with an increase in

$$\sqrt{\frac{L^2/\alpha}{P}}$$

where, (3)
L = wall thickness, m (ft)
P = length of dynamic cycle, hr (hr)
α = thermal diffusivity, m²/hr (ft²/hr)

Comparing walls of equal thickness L, subjected to the same dynamic cycle P of 24 hours, then thermal lag is proportional to

$$\sqrt{\frac{1}{\alpha}}$$

and a direct comparison of the thermal lag of the Wall C2 (lightweight concrete) to Wall C1 (normal weight concrete) would be:

$$\sqrt{\frac{1}{\alpha_{LW}}} \div \sqrt{\frac{1}{\alpha_{NW}}} = \sqrt{\frac{\alpha_{NW}}{\alpha_{LW}}} \qquad (4)$$

For the three walls tested and the thermal diffusivity values from Table 2, this ratio would be:

- The thermal lag of C2 would be 1.5 times that of wall C1
- The thermal lag of C3 would be 2.1 times that of wall C1

In the dynamic tests conducted at CTLGroup as shown in Table 3, the measured thermal lags for walls C2 and C3, respectively, were 1.4 and 2.1 times the thermal lag for wall C1 (normal weight concrete), and therefore consistent with theoretical calculations. In a similar fashion an estimate of the theoretical increase in thermal lag obtained by reducing the density of the concrete masonry walls from 1830 kg/m³ (114 lb/ft³), as for Specimen No. S1, to 1510 kg/m³ (94 lb/ft³), as for Specimen No. S2, would be approximately a 17%.

6. THERMAL MASS VERSUS THERMAL INERTIA

Thermal mass describes the ability of a wall to store heat whereas thermal inertia describes the heat flow through a wall including its heat storage. Thermal mass is quantified by heat capacity, and for a homogeneous wall, is the product of the specific heat, density, and thickness. Higher concrete densities and thicker walls provide higher heat capacities and therefore result in more heat storage. However, thermal inertia combines the effect of heat storage with the movement of heat through a wall. Thermal inertia is characterized by thermal diffusivity – the combination of heat capacity for a unit thickness and thermal conductivity.

For an exterior single layer uninsulated concrete or masonry wall, the beneficial effects of thermal inertia, as characterized by the reluctance to change temperature (as a result of lower diffusivity), are increased when density is reduced. These lower density concretes have enough density to provide thermal mass effects while having a lower thermal conductivity than normal weight concrete. These combine to provide a lower thermal diffusivity.

7. OPTIMUM CONCRETE DENSITY FOR MAXIMUM THERMAL INERTIA

Change in thermal diffusivity with respect to concrete density is not linear, because thermal conductivity increases exponentially when compared to increases in density while specific heat remains relatively constant (with some reported variation). Therefore, the impacts of thermal inertia of concrete walls (thermal lag, amplitude reduction, lowering total energy) are more significant when density is reduced as with structural lightweight, insulating lightweight and aerated lightweight concretes. Indeed, if the Valore formula for thermal conductivity from Eq. 1 is inserted into the diffusivity from Eq. 2, then the relationship between thermal lag and concrete density would be:

(SI) $\sqrt{(1/\alpha)} = \sqrt{((D \cdot c)/k)} = \sqrt{((D \cdot c)/\, 0.0865 \cdot e^{0.00125D})}$

(IP)

$$\sqrt{\frac{1}{\alpha}} = \sqrt{\frac{Dc}{k}} = \sqrt{\frac{Dc}{0.6e^{0.02D}}}$$

Then, to solve to find the optimum, differentiate thermal lag with respect to density and set the results to zero. The result is that a concrete density of 800 kg/m³ (50 lb/ft³) will provide maximum thermal lag [12]. The solution is shown graphically in Figure 2**.**

8. IECC AND ASHRAE 90.1

The *IECC 2012* provides decreased R-value requirements for above-grade mass walls compared to frame walls in commercial buildings. Section 402.2.3 on above-grade walls, in Chapter 4 "Commercial Energy Efficiency," states that "Mass walls shall include walls weighing at least (1) 35 psf (170 kg/m²) of wall surface area; or (2) 25 psf (120 kg/m²) of wall surface area if the material weight is not more than 120 pounds per cubic foot (pcf) (1900 kg/m³)" [1]. Similarly, *ASHRAE 90.1-2012* defines a mass wall as a wall with a heat capacity "exceeding (1) 7 Btu/ft^2·°F (143 kJ/m^2·K) or (2) 5 Btu/ft^2·°F (102 kJ/m^2·K), provided that the wall has a material unit weight not greater than 120 lb/ft^3 (1920 kg/m³)" [2]. The analysis in this paper provides justification for the lower thresholds for mass walls for lower density materials. As shown earlier, decreasing concrete density results in the increase of **BOTH** steady-state thermal resistance and thermal inertia as expressed in thermal lag, reduction in amplitude, and energy transfer.

For a typical 200-mm (8-in.) thick, single width uninsulated concrete masonry wall, a minimum CMU density of approximately 1280 kg/m³ (80 lb/ft³) qualifies as a mass wall according to the *IECC* and *ASHRAE 90.1*. For a solid concrete wall, 150 mm (6 in.) of 800 kg/m³ (50 lb/ft³) concrete qualifies as a mass wall according to the *IECC* and *ASHRAE 90.1*. Compliance with these documents does not require the mass to be on any particular side of insulation in a wall – mass can be on the inside, outside, inside and outside, within, or integral to insulation in the wall.

Results in this paper are for properties of homogeneous walls. The effects of a wall's thermal inertia on overall energy performance of a building are complex and difficult to reduce to one factor. This is because of the significant influence of variables, beyond the scope of this paper, which include: the location of insulation (interior, exterior, or integral), the entire building envelope, building orientation and operation, and daily and annual weather conditions.

9. CONCLUSIONS

1.) For the test results reported, the steady-state thermal resistance (R-value) to heat flow through single layer uninsulated walls made from ready-mixed concrete and zero slump CMU concrete increases with decreasing density.

2.) For the test results reported, the resistance to heat flow for dynamic temperature conditions through single layer uninsulated concrete walls increases with decreasing density.

3.) Thermal inertia as represented by thermal lag, amplitude reduction, and reduced energy transfer, increases with decreasing thermal diffusivity.

4.) The increase in thermal inertia with respect to concrete density is not linear, because of the exponential increase in thermal conductivity when compared to the decrease in density.

5.) The optimal concrete density for thermal inertia is 50 lb/ft³ (800 kg/m³). Structural lightweight concrete and CMU in the range of 1360 to 2080 kg/m³ (85 to 130 lb/ft³) also show improved thermal inertia compared to normal weight concrete in the range of 2080 to 2400 kg/m³ (130 to 150 lb/ft³). Concrete densities below 1360 kg/m³ (85 lb/ft³) are generally not load-bearing, structural concrete.

6.) Measured energy consumption through walls as shown in Table 3 is reduced when the steady-state and dynamic thermal resistance are improved by lower concrete densities, thereby reducing energy consumption for heating and cooling energy and helping the sustainability of critical energy sources.

7.) USACE test procedures (CRD-C 36) for determination of thermal diffusivity may be used on zero slump CMU concrete samples made with materials taken from the mixers of commercial CMU plants.

8.) The *IECC 2012* requirement of a lower wall weight (400 vs. 560 kg/m³ (25 vs. 35 lb/ft³)) for mass walls and the *ASHRAE 90.1-2010* definition of a lower heat capacity (143 vs. 102 kJ/m^2·K (7 vs. 5 Btu/ft^2·°F)) for concrete densities less than 1920 kg/m³ (120 lb/ft³) for mass walls, is a simple and effective approximation of the influence of the reduction in thermal diffusivity, and hence enhanced thermal inertia of lower density concrete and concrete masonry.

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Table 1 Thermal Conductivity for Concretes of Differing Densities as Measured From Small Sized Specimens and Full Sized Walls (Excerpted from Reference [4]).

	C1 Normal Weight Concrete	**C2 Structural Lightweight Concrete***	**C3 Insulating Non-Structural Concrete**
Density, kg/m^3 (lb/ft^3) Fresh	2350 (147)	1650 (103)	900 (56)
Density, kg/m^3 (lb/ft^3) Air Dry	2290 (143)	1590 (99)	770 (48)
Density, kg/m^3 (lb/ft^3) Oven Dry	2240 (140)	1510 (94)	740 (46)
Thermal Conductivity measured by method indicated, W/m·K (Btu·in/h·ft^2·°F)			
Guarded Hot Plate (ASTM C 177) at 21 ºC (70 ºF)	2.32 (16.1)	0.65 (4.5)	0.20 (1.4)
Hot Wire, at % moisture content	3.07 (21.3) @3.1%	0.99 (6.9) @9.5%	0.45 (3.1) @28.9%
Hot Wire, oven dry	1.96 (13.6)	0.60 (4.2)	0.22 (1.5)
Calibrated Hot Box (ASTM C 976), at 11±2ºC (52±3ºF)	1.67 (11.6)	0.68 (4.7)	0.20 (1.4)

*Structural lightweight concrete composed of both coarse and fine rotary kiln produced expanded shale lightweight aggregate.

**Insulating concrete composed of expanded perlite aggregate.

Table 2 – Results of Thermal Diffusivity Tests Measured on Structural Concretes and Zero Slump CMU Concrete of Different Densities

Specimen No.	**Tested by**	**Concrete Type**	**Density, kg/m^3 (lb/ft^3)**	**Thermal Diffusivity, m^2/s x 10^{-7} (ft^2/hr)**
S1	Solite Corp	Structural lightweight 31 MPa (4.5 ksi), air dry	1830 (114)	5.7 (0.022)
S2	Solite Corp	Structural lightweight 28 MPa (4.1 ksi), air dry	1510 (94)	4.1 (0.016)
S3*	Solite Corp	Test No. S1 oven dried and coated	1710 (107)	5.9 (0.023)
S4*	Solite Corp	Test No. S2 oven dried and coated	1440 (90)	4.4 (0.017)
S5	Solite Corp	ASTM C 90 CMU concrete	1440 (90)	4.1 (0.016)
S6	Solite Corp	ASTM C 90 CMU concrete	2070 (129)	9.3 (0.036)
C1	CTL [5]	Structural normal weight concrete	2290 (143)	9.5 (0.037)
C2	CTL [6]	Structural lightweight Concrete	1590 (99)	4.0 (0.0155)
C3	CTL [7]	Insulating concrete	900 (56)	2.2 (0.00849)

*The test numbers S3 and S4 were conducted on specimen numbers S1 and S2 after oven drying and then coating the specimens with a waterproof epoxy.

Table 3 – Excerpt from Table 5 "Summary of Dynamic Test Results for NBS-10 Test Cycle" [4]

Wall No./ Density, (kg/m³) lb/ft³	Thermal Lag, hours			Reduction in Amplitude Average, %	Ratio of Total Energy, %	Measured Energy Transfer, W·hr/hr
	Based on Temperature, range	Based on Maximum Heat Flow, range	Average			
C1/ 2290 (143)	3 to 4.5	3 to 4.5	4	45	66	4342
C2/ 1590 (99)	5 to 6	5 to 6	5.5	54	60	2510
C3/ 900 (56)	7 to 8.5	9	8.5	63	53	909

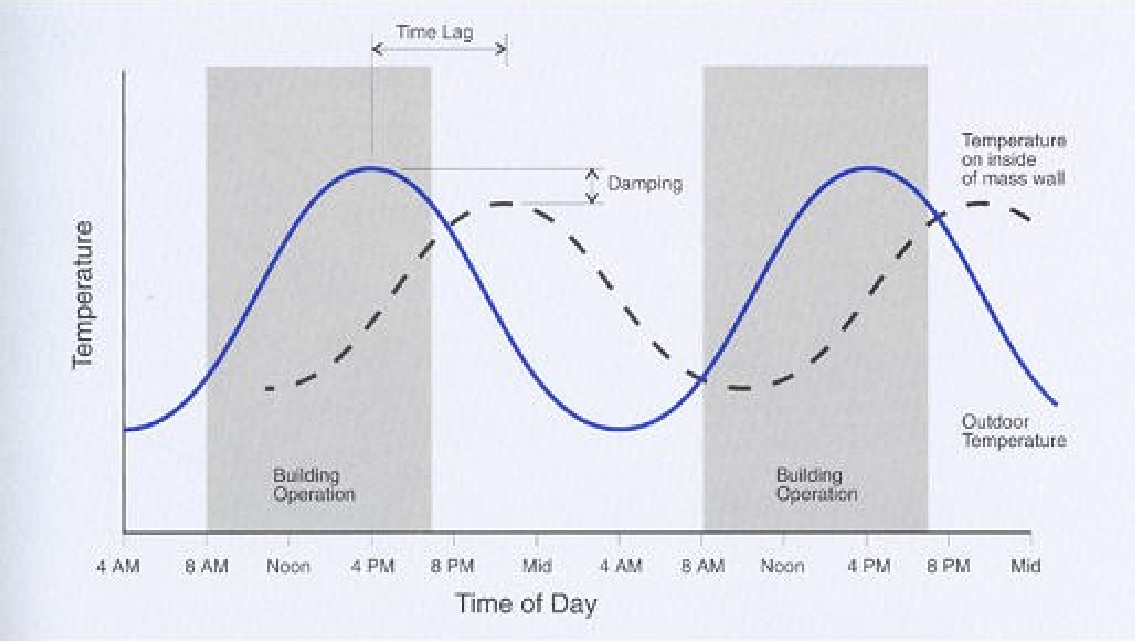

Figure 1 Time lag and temperature damping [11]

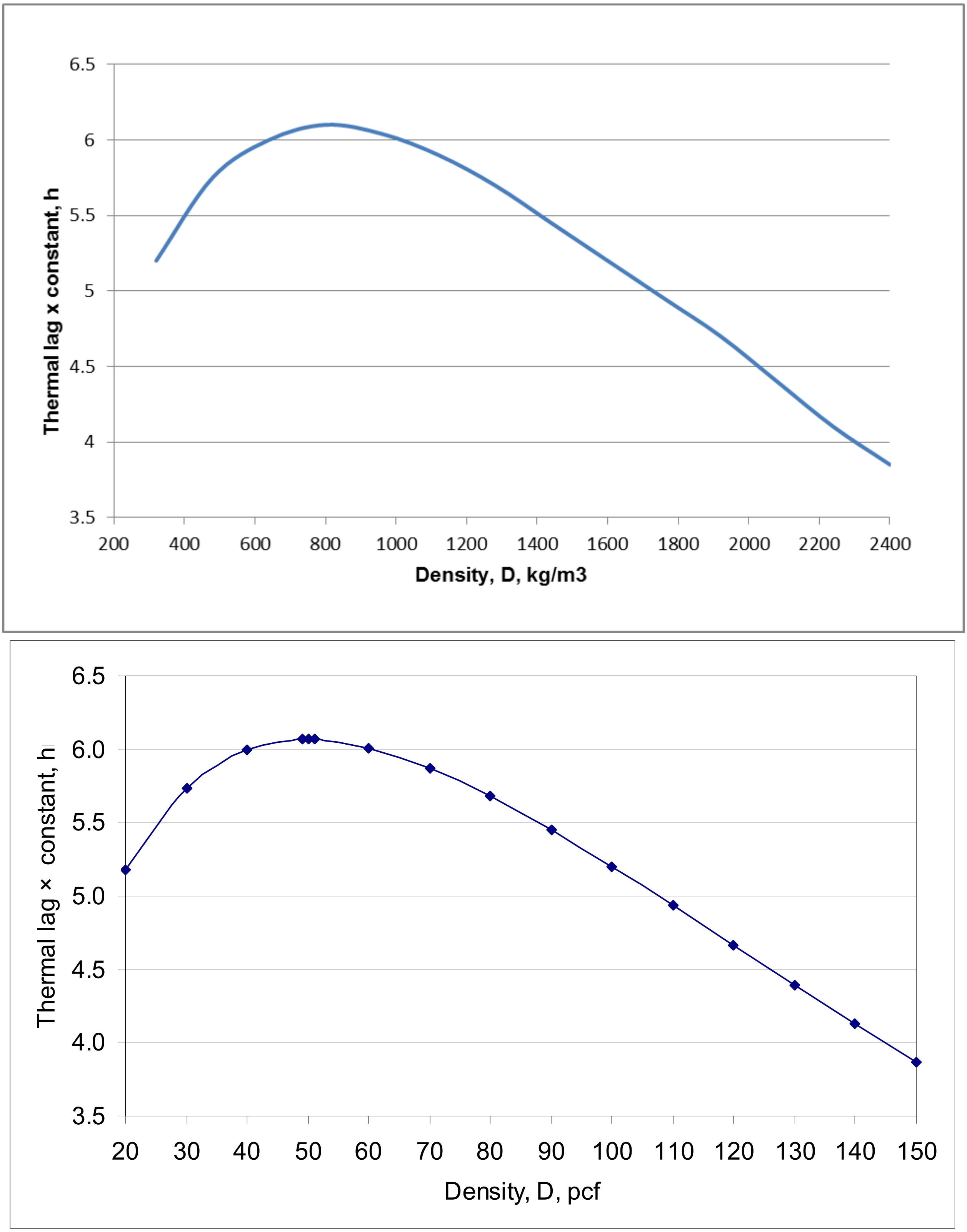

Figure 2 Graphical solution of optimum concrete density for maximum thermal lag