STEADY-STATE THERMAL PERFORMANCE OF CONCRETE MASONRY UNIT WALL SYSTEMS

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ABSTRACT

New materials, modern wall technologies now available in the building marketplace, and unique, more accurate, methods of thermal analysis of wall systems create an opportunity to design and erect buildings where thermal envelopes that use masonry wall systems can be more efficient.

Current techniques for the evaluation of wall thermal performance are focused on the thermal resistance value of the clear wall area. The clear wall is the flat, uniform part of the wall, uninterrupted by wall details. Traditionally, only this area is tested and most of the theoretical calculations are provided only for this area. Here, the thermal performance of six masonry wall systems is analyzed. Most existing masonry systems are modifications of technologies presented in this paper. Finite-difference two-dimensional and three-dimensional computer modeling and unique methods of the clear wall and overall thermal analysis were used.

In the design of thermally efficient masonry wall systems it is important to know how effectively the insulation material is used and how the insulation shape and its location affect the wall thermal performance. For some shapes of the insulation and concrete components, hidden thermal shorts can cause considerable heat losses. In this study, the thermal analysis of the clear wall was enriched with the study of a quantity defined herein as the thermal efficiency of the insulation material. Also, an evaluation of the thermal effects generated by mortar and grout was included in the clear wall thermal analysis.

In addition, an examination of thermal properties of wall details was performed for three wall systems. The total wall system thermal performances were determined for a typical single-story ranch house. At present, building energy codes and standards and many residential building designers do not include the effects of building envelope details such as corners, window and door openings, and structural joints with roofs, floors, ceilings, and other walls. This simplification can lead to errors in determining the energy efficiency of the building envelope. In masonry wall systems, wall details may have a structure different from the clear wall area. Also, highly conductive grout and reinforcement are used very often. These cause additional thermal bridges, which should be incorporated into the thermal performance analysis.

INTRODUCTION

A steady-state thermal analysis has been performed on popular masonry wall systems and their details. A finite-difference heat conduction code developed at a national laboratory was used for thermal modeling (Childs 1993). The accuracy of the prediction of clear wall R-values was validated by using 19 published test results for masonry, wood-framed, and metal-stud walls (maximum discrepancy between test results and simulated R-values was less than 6%). Considering that the precision of the guarded hot box method is reported to be approximately 8% (ASTM 1989), the ability of the computer model to reproduce the experimental data was found to be satisfactory.

Figure 1 illustrates 12 in. (30 cm) thick masonry wall units that were analyzed for this paper. In the clear wall thermal analysis, the following six concrete masonry units (CMUs) were studied: solid block, two-core hollow block, cut-web block, multicore block, solid block with interlocking insulation insert, and solid block with serpentine insulation insert. The thermal resistance for each unit was estimated for five different values of concrete thermal resistivity: 0.19 (1.32), 0.28 (1.94), 0.40 (2.77), 0.59 (4.09), and 0.86 $h \cdot ft^2 \cdot °F/Btu$ per in. ($5.96\ m \cdot K/W$). These values approximately correspond, respectively, to the following densities of concrete: 120 (1,920), 100 (1,600), 80 (1,280), 60 (980), and 40 lb/ft^3 ($640\ kg/m^3$) (ASHRAE 1993).

Typically, CMUs are produced in the United States with normal density concrete—140-120 lb/ft^3 (2,240-1,920 kg/m^3). Using normal density concrete, hollow blocks can be manufactured in compressive strengths ranging from 1,500 to 4,000 psi (10 to 27.5 Mpa) based on net area (Drysdale et al. 1994).

In addition to this traditional production, a variety of shapes of CMUs made of lightweight concretes are available in several countries. Concretes with lower thermal conductivities improve the thermal performance of such

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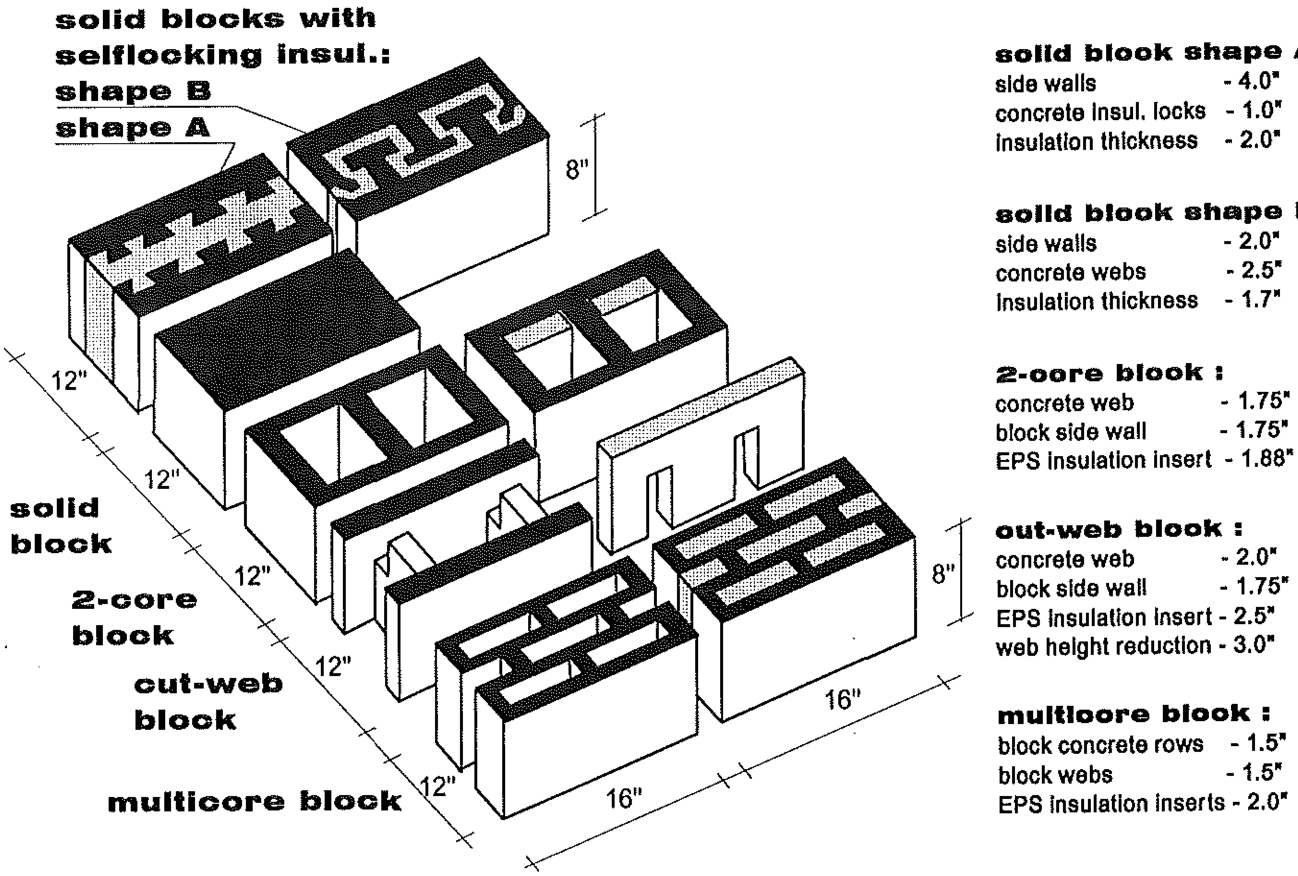


Figure 1 *Simulated masonry wall systems.*

units. Unfortunately, lower compressive strength reduces the load that can be carried by walls made of CMUs manufactured of lightweight concretes. Compressive strengths of lightweight concretes are sometimes 10 times lower than for normal density concretes—ranging from 290 to 1,500 psi (2 to 10 Mpa) (Roszak and Kubiszek 1989; RILEM 1993; Mielczarek and Lange 1989). So lightweight concretes are mostly used to produce solid CMUs or left-in-place forms where necessary strength is provided by poured structural concrete.

The most popular lightweight concretes are listed below:

Expanded shale, clay, and slate (ESCS) concretes of densities of 80 to 100 lb/ft^3 (1,600 to 1,280 kg/m^3) are also used in the U.S. for CMU production. For thermal calculations for CMUs made of these concretes, the following range of thermal resistivities is recommended: 0.40 to 0.27 h·ft^2·°F/Btu per in. (2.79 to 1.89 m·K/W) (ESCSI 1992).

In Europe, *lightweight expanded clay aggregate (LECA) concrete*—28 to 40 lb/ft^3 (450 to 640 kg/m^3)—is widely used for CMU production. The thermal resistivity of the LECA concrete is reported as between 1.07 and 0.9 h·ft^2·°F/Btu per in. (7.70 and 6.29 m·K/W) (LECA 1991).

Also, mostly in Europe, CMUs are made of *wood concrete*—28 to 40 lb/ft^3 (500 to 1,000 kg/m^3). The thermal resistivity of wood concrete is reported as between 0.90 and 0.41 h·ft^2·°F/Btu per in. (9.09 and 2.86 m·K/W) (Mielczarek 1989; Nanazasvili 1983; Wyszynski and Sadowski 1985; Kosny 1994).

Expanded polystyrene beads are used sometimes as lightweight aggregates for concrete production. Density of the *expanded polystyrene bead concrete* is in the range of 25 to 70 lb/ft^3 (400 to 1,120 kg/m^3). A proposal of the Canadian 1995 National Energy Code recommends, for the expanded polystyrene bead concrete of density of 30 lb/ft^3 (480 kg/m^3), a thermal resistivity of 0.89 h·ft^2·°F/Btu per in. (6.17 m·K/W) (NRCC 1995).

Autoclaved aerated concrete (AAC) is a popular material for solid CMU production in Europe. The density of the CMUs made of AAC is in the range of 30 to 40 lb/ft^3 (480 to 640 kg/m^3); its thermal resistivity is about 0.95 h·ft^2·°F/Btu per in. (6.58 m·K/W) (RILEM 1993).

The mortar joint area usually covers 4% to 10% of the total wall area. Mortar may generate considerable heat losses in masonry walls. Also, the construction of load-bearing walls made of hollow-core blocks often requires installing additional reinforcement and filling air cores with the grout. The evaluation of the thermal effects generated by mortar and grout were included in the clear wall thermal analysis.

Existing methods of thermal calculations for building wall systems are based only on the measured or calculated thermal performance of the clear wall area. Clear wall measurements are typically carried out by apparatus such as the one described in ASTM C 236 (ASTM 1989). A relatively large (approximately 8 ft by 8 ft or larger) cross section of the clear wall area of the wall system is used to determine its thermal performance. Thermal anomalies, such as concrete webs or core insulation inserts, are typically included in the test configuration. For concrete and masonry walls, building envelope intersections and opening perimeters may represent different constructions than those of the clear wall area. Obviously, the thermal properties measured or calculated for the clear wall area may not adequately represent the total wall system thermal performance. In the past, that fact has often been omitted, and, as a result, wall details have not been thermally examined and improved. As was discussed in Kosny and Desjarlais (1994) for the cases of wood and metal frame walls, polystyrene foam wall form systems, and two-core CMU walls, these simplifications can lead to errors in determining the energy efficiency of the building envelope. Investigating areas of possible heat losses in buildings and opportunities to replace highly conductive materials should aid thermal designing of future buildings.

Three masonry wall systems were considered for the overall wall analysis (two-core, cut-web, and multicore units). For each wall system, models of the clear wall area, corner, wall/ceiling (roof/wall) intersection, wall/floor intersection, window header, window sill, window edge, door header, and door edge were analyzed. For all these wall systems, two densities of concrete were considered during modeling:

- for two-core and cut-web units: normal density concrete, 120 lb/ft^3 (1,920 kg/m^3) of thermal resistivity 0.19 h·ft^2·°F/Btu per in. (1.32 m·K/W);
- for multicore units: lightweight concrete, 40 lb/ft^3 (640 kg/m^3) of thermal resistivity 0.90 h·ft^2·°F/Btu per in. (6.24 m·K/W).

Geometries of wall details were obtained from the following standard architectural drawings or system manufacturers' design guides: NCMA (1975), Hoke (1988), IBC (1992), and SII 1989, 1991).

The temperatures used in all of the modeling runs were 70°F (21°C) for the interior space and −20°F (6.6°C) for the exterior environment. The resultant temperature maps were used to calculate average heat fluxes and the wall system R-values. Using a standard building elevation, these results have been combined to compute the amount of the clear wall area and to determine the overall wall system thermal performance for a typical single-story ranch house.

WALL STEADY-STATE THERMAL MODELING AND CLEAR WALL R-VALUE CALCULATIONS

A finite-difference computer code was used to analyze the heat transfer in the clear walls and wall details. It can solve steady-state and/or transient heat conduction problems in one-, two-, or three-dimensional Cartesian coordinates (Childs 1993). Multiple materials and time- and temperature-dependent thermal conductivity, density, and specific heat can be specified. Two-dimensional modeling was used for most of the clear wall areas. For some elements of wall openings and for areas of wall intersections with other building structure components, three-dimensional modeling was necessary. Resulting temperature maps were used to calculate average heat fluxes and the wall system R-values.

The accuracy of predicting clear wall R-values was confirmed by using 19 published test results for masonry, wood-framed, and metal-stud walls. The phrase "clear wall" was previously defined by Kosny and Desjarlais (1994) as the flat part of the wall system that is free of thermal anomalies due to building envelope details such as corners, door and window openings, and structural joints with roofs, floors, ceilings, and other walls. The comparison between experimental and simulated R-values is presented in Table 1. The 95% confidence interval of the guarded hot box method used for the experiments is reported to be about ±8% (ASTM 1989). The results of the computer modeling should be within this band to be considered as credible predictions.

In Table 1, the data presented in the "Accuracy" column were computed based on the following formula:

$$\text{Accuracy} = \frac{R_{simul} - R_{test}}{R_{test}} \cdot 100\%. \tag{1}$$

As shown in Table 1, the maximum discrepancy between test results and simulated R-values was less than 6%. Considering that the precision of the guarded hot box method is reported to be approximately 8% (ASTM 1989),

TABLE 1 **Accuracy of Heating 7.2 Clear Wall R-Value Calculations**

Source of Information	No. of Considered Walls	Wall Description	Accuracy (%)
1. Valore (1988)	4	Empty 2-core, 30 cm (12 in.) CMU	3.6
2. Valore (1988)	6	Filled 2-core, 30 cm (12 in.) CMU	5.6
3. Van Geem (1986)	1	Empty 2-core, 30 cm (12 in.) CMU	−0.3
4. Van Geem (1986)	1	Filled 2-core, 30 cm (12 in.) CMU	−3.6
5. James (1990)	1	Empty 2-core, 30 cm (12 in.) CMU	−0.9
6. James (1990)	1	Filled 2-core, 30 cm (12 in.) CMU	0.8
7. James (1990)	1	2 × 4 wood-framed wall	1.6
8. Brown (1993) Strzepek (1990)	4	Metal stud walls, 40 cm (16 in.) o.c.	5.2

the ability of this computer model to reproduce the experimental data was found to be satisfactory.

THERMAL EFFICIENCY OF INSULATION MATERIAL USE

Because thermal insulation inserts are expensive components of masonry wall units, it is important to effectively use the insulation material. Knowing the thermal efficiency (*TE*) of the insulation material in masonry units can aid in the thermal evaluation of existing concrete masonry systems. Knowing how much the insulation material used in the wall affected the wall's thermal performance may also be useful in the design of thermally efficient masonry wall systems containing interstitial insulation.

Many masonry technologies are available that contain several types of interstitial insulation inserts. Very often, if the thermal resistance of the insulation used in the CMU and the increase of the wall R-value caused by this insulation are compared, the actual increase of the wall thermal resistance is much lower than the potential R-value of the used insulation (Kosny and Christian 1993). This is a result of the insulation material being used in an inefficient way so that hidden thermal shorts cause heat losses. The method of estimating its value is based on comparison of the R-values of insulated R_i and uninsulated R_u units, each having the same face area (F_u). The equivalent R-value of the insulation inserts (R_e) can be calculated for the layer of insulation material having the same face surface area, F_u, as the CMU under consideration and containing the same volume, V_{ins}, which is used to insulate the CMU. *TE* may be expressed by the following equation:

$$TE = \frac{R_i - R_u}{R_e} \cdot 100\% \tag{2}$$

where

R_i = R-value of insulated unit,
R_u = R-value of uninsulated unit, and
R_e = equivalent R-value of insulation material used.

To get the equivalent thickness of insulation (d_e), the insulation volume, V_{ins}, is divided by the face surface area, F_u, of the CMU. Equivalent thickness, d_e, can be expressed as follows:

$$d_e = \frac{V_{ins}}{F_u}. \tag{3}$$

The equivalent R-value of the consumed insulation material, R_e, is

$$R_e = d_e \cdot r_i \tag{4}$$

where

r_i = thermal resistivity of insulation material.

The *TE* of the insulation material describes the influence of the shape of the concrete and insulating parts of the wall unit on the wall R-value.

CLEAR WALL AND OVERALL WALL THERMAL PERFORMANCE

Currently, the evaluation of wall thermal performance is based on the thermal resistance value of the clear wall area. The clear wall is a flat, uniform part of the wall, uninterrupted by wall details. Traditionally, only this area is tested and most of the theoretical calculations are provided only for this area. Measured or calculated thermal properties of the clear wall area may not adequately depict the total wall system thermal performance. For concrete masonry wall systems, intersections with other building elements and perimeters of openings are often very different from the clear wall. In the past, this fact has been ignored and omitted in wall thermal analysis.

The influence of wall details on the overall wall thermal performance is different for every structure because of the variety of architectural designs. To allow comparisons, a standard building elevation was used. The standard elevation selected for this purpose is a single-story ranch-style house that has been the subject of previous energy-efficiency modeling studies (Huang et al. 1987). The house has approximately 1,500 ft^2 of living area (55 by 28 ft), 1,328 ft^2 of exterior wall area (elevation), eight windows, and two doors (one door is a glass slider and is included with the windows). The elevation wall area includes 1,146 ft^2 of opaque wall area (an overall wall), 154 ft^2 of windows, and 28 ft^2 of door area. Based on the computed wall detail R-values, the overall wall system R-value was calculated by combining the thermal resistance of the wall details, subsystems, wall intersections, and clear wall area in a parallel, area-weighted method:

$$R_{ow} = \left[\sum_{i=1}^{i=n}\left(w_i \cdot \frac{1}{R_i}\right)\right]^{-1} \tag{5}$$

where

R_i = R-value of wall component (detail or clear wall),
I = wall component index,
n = number of wall components, and
w_i = wall component area-weighting factor,

where

$$w_i = \frac{\text{area of component}}{\text{overall wall area}}. \tag{6}$$

The amount of clear wall area was calculated by determining the zone of influence for each wall detail and subtracting that area from the total exterior wall area. The zone of influence was determined by examining the isotherms produced by the modeling runs. The zone of influence was defined as that area where the existence of the detail changed the slope of the isotherm by more than 5 degrees. This slope represents approximately a 1°F change in temperature per inch of length along the wall surface. The area that depicted isotherms that were impacted by the presence of the wall detail was defined as the zone of influence for that detail.

Very often, the thermal performance of wall details is different from that of the clear wall area. Distribution of heat losses through the wall details can be different from the wall area distribution. For an ideal wall system (from a thermal performance perspective), the overall wall R-value should be equal to the clear wall R-value.

RESULTS OF STEADY-STATE THERMAL MODELING

Clear Wall Thermal Analysis

For clear wall thermal analysis, six types of masonry wall units were considered during computer modeling. For each shape of CMU, thermal efficiency of insulation (*TE*) and clear wall R-value were computed as a function of thermal resistivity of concrete used in block production. A reduction of wall R-value caused by using mortar was discussed as a function of thermal resistivity of block concrete for uninsulated and insulated two-core units. For uninsulated two-core units, insulated two-core units, cut-web units, uninsulated multicore units, and insulated multicore units, a reduction of the wall R-value caused by grout was computed as a function of thermal resistivity of block concrete. Overall wall thermal analysis was performed for uninsulated two-core units, insulated two-core units, cut-web units, uninsulated multicore units, and insulated multicore units. Structural drawings of the wall details for solid CMUs and for solid CMUs with the serpentine and interlocking insulation inserts were not available to the authors, so they were not included in the overall wall analysis.

As shown in Figure 2, the thermal efficiency (*TE*) of the insulation material in two-core, cut-web, and multicore units made of normal-density concretes varies from 20% to 40%. For solid units with interlocking insulation inserts (shape B), *TE* varies from 30% to 80%, and for shape A units, it varies from 70% to 90%. It can be observed that if CMUs are made of lightweight concretes, the thermal efficiency of the insulation is higher. For most insulated blocks made of lightweight concrete (except insulated multicore CMUs), *TE* can reach 60% to 90%. Insulation in multicore units is very ineffective. For normal-density concrete, it is less than 20%. The maximum *TE* value for these multicore units made of very lightweight concrete likely will not exceed 65%.

Thermal resistances of six considered shapes of CMUs are depicted in Figure 3 as a function of thermal resistivity of block concrete.

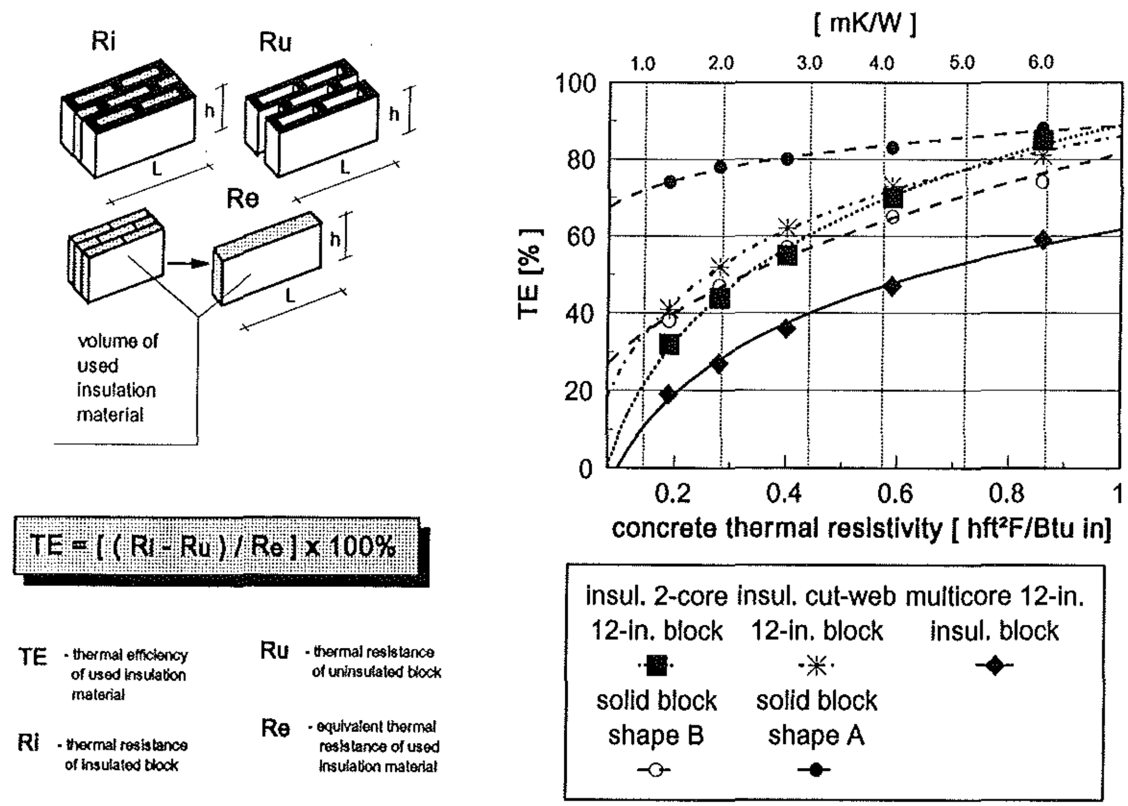


Figure 2 *Thermal efficiency—TE of insulation material in masonry units.*

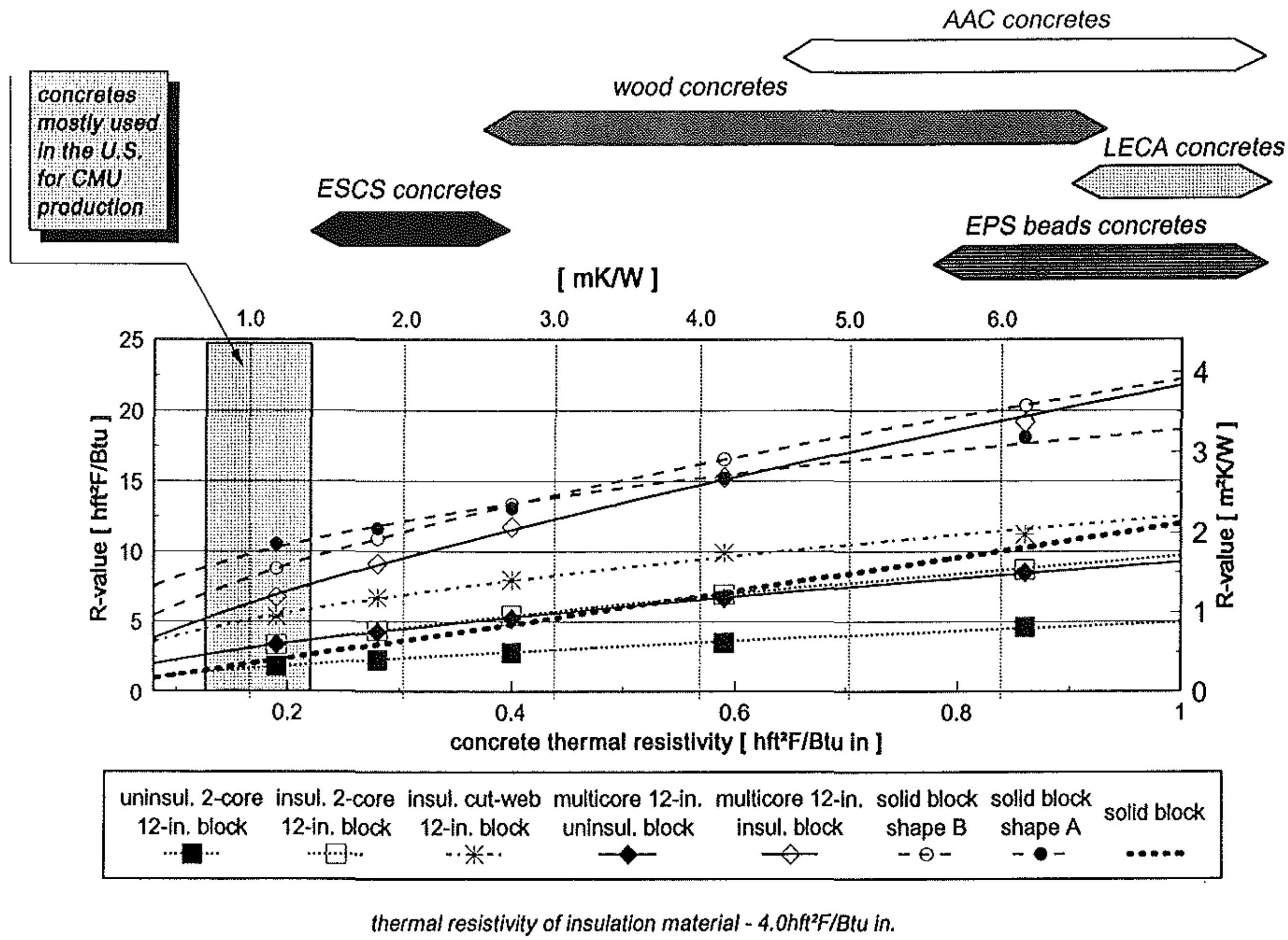


Figure 3 *Thermal resistance of masonry units.*

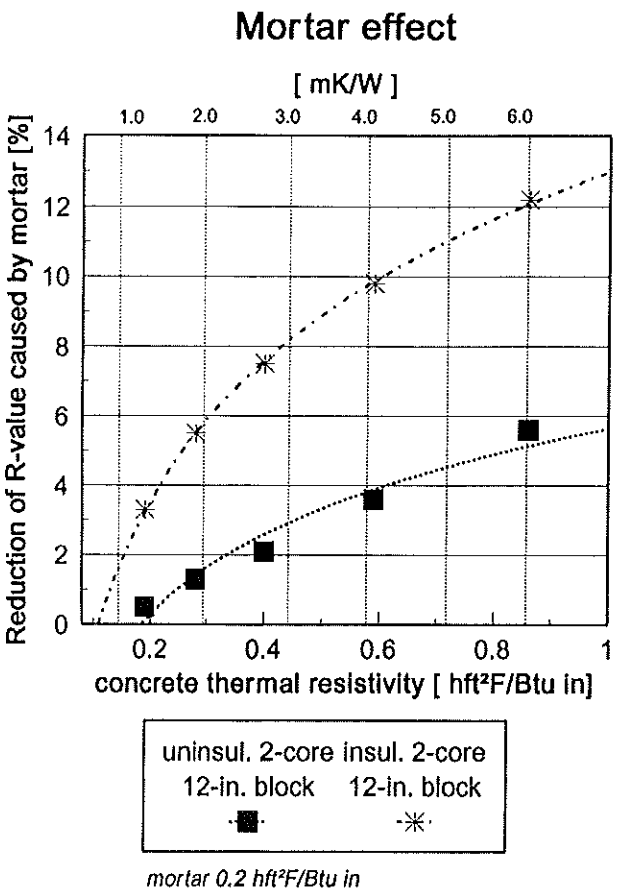
Solid CMUs are normally produced of the lightweight concretes. For 12-in.-thick units, R-value varies from about 5 to 10 h·ft²·°F/Btu (0.8 to 1.7 m²·K/W).

As shown in Figure 3, the thermal performance of *two-core units* made of normal-density concretes is very low; for an uninsulated 12 in. (30 cm) thick unit, the R-value is less than 2 h·ft²·°F/Btu (0.35 m²·K/W). Because of this, several companies offer many types of insulation inserts that are supposed to improve the block's thermal performance. Unfortunately, because the inserts are located only in air cavities portioned with the concrete webs, they cannot eliminate the thermal shorts through the transversal concrete webs. For insulated units, the R-value remains less than 3.5 h·ft²·°F/Btu (0.62 m²·K/W). If two-core units are made of lightweight concretes (not a common practice in the U.S.), their R-values may be higher—about 4 h·ft²·°F/Btu (0.7 m²·K/W) for uninsulated units and 8 h·ft²·°F/Btu (1.4 m²·K/W) for insulated units.

Cut-web CMUs were designed to reduce heat losses caused by transversal concrete webs in two-core units. Many types of the insulation inserts for the cut-web units are available in the U.S. market. Even if the concrete web height is radically reduced (about 40% in simulated cut-web units), heat losses still occur through the transversal concrete webs. It can be observed in Figure 3 that the increase of the thermal resistance caused by the reduction of concrete webs is minimal for units made of normal-density concretes (comparison of R-value between insulated two-core and cut-web units). For the insulated 12-in.-thick cut-web unit made of normal-density concrete, the R-value is less than 5.4 h·ft²·°F/Btu (0.95 m²·K/W). R-values of the cut-web units made of lightweight concrete could exceed 11 h·ft²·°F/Btu (1.94 m²·K/W).

As shown in Figure 3, for *multicore units* made of normal-density concretes, the R-value of an uninsulated 12 in. (30 cm) thick unit is less than 3.5 h·ft²·°F/Btu (0.62 m²·K/W) and for an insulated unit it is about 6.8 h·ft²·°F/Btu (1.2 m²·K/W). It is interesting that the R-value of an uninsulated multicore unit is as high as the R-value of an insulated two-core unit. For insulated multicore units made of lightweight concrete, the R-value could exceed 19 h·ft²·°F/Btu (3.35 m²·K/W).

Solid blocks with interlocking insulation inserts are usually made of lightweight concretes. As shown in Figure 3, for solid units with integral insulation inserts (shape A), the R-value can exceed 18 h·ft²·°F/Btu (3.17 m²·K/W.



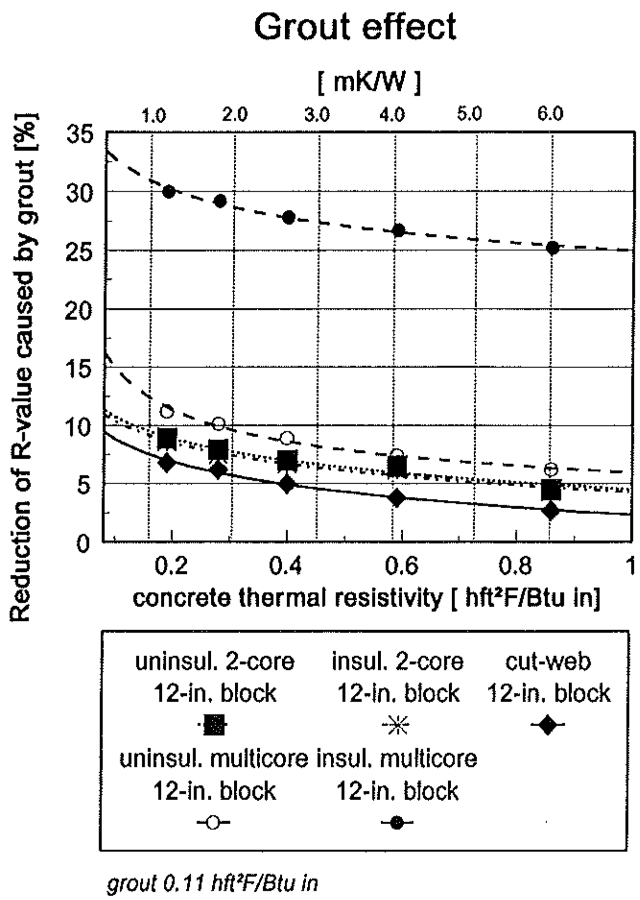


Figure 4 *Reduction of wall R-value caused by mortar and concrete poured into cores (grout) in masonry units.*

For a shape B unit, the R-value can reach 20 h·ft²·°F/Btu (3.52 m²·K/W).

Note that all presented R-values account only for blocks themselves. They do not account for mortar or grout.

Mortar Effect

The mortar joint area usually covers 4% to 10% of the total wall area. Mortar may generate additional wall heat losses in masonry walls. Because of the complicated three-dimensional character of the heat transfer in areas of mortar joints, the reduction of the wall thermal resistance is seldom incorporated in the R-value calculations. As shown in Figure 4, the R-value reduction can exceed 12% for two-core units. The mortar effect increases when the thermal resistivity of block concrete increases. A reduction of the influence of the heat losses through the mortar on the wall R-value can be achieved by using less conductive mortars or decreasing the area of mortar joints. In many CMUs, side mortar is being replaced by interlocking means to connect adjacent units without the use of mortar.

Grout Effect

Construction of load-bearing walls made of hollow-core blocks frequently requires installing additional reinforcement and filling air cores with the grout. For all CMUs, the grout effect decreases when the concrete thermal resistivity increases. For the grout of thermal resistivity of 0.11 h·ft²·°F/Btu per in. (0.77 m·K/W), the grout effect was depicted as a function of the block concrete thermal resistivity. It can be observed in Figure 4 that cut-web units are less sensitive to the grout effect (the grout effect varies from 3% to 7%). For two-core units made of normal-density concretes, reduction of the R-value caused by the grout poured into the cores is about 10%. For two-core units made of lightweight concrete, the grout effect is about 5%. For uninsulated multicore CMUs, the grout effect remains in the range of 6% to 12%. The R-value of insulated multicore units is very sensitive to the local thermal bridges caused by cores filled with grout. Reduction of the R-value for these units may reach 30% for normal-density concretes and 25% for lightweight concretes.

Overall Wall Thermal Analysis

Walls are not homogeneous thermal barriers made from uniform components. Wall details, such as corners or structural connections between wall and ceiling, behave very differently from the clear wall. For example, in walls constructed of cut-web units, standard two-core units have to be used for corners and wall openings (IBC 1992). In all masonry systems, U-blocks are frequently used in bond beams and cast-in-place lintels (Hoke 1988; SII 1991). Steel lintel angels are commonly used for window and door headers (SII 1991). Also, for most masonry wall systems, beams, girders, and other concentrated loads shall bear on the grouted blocks [Hoke 1988; NCMA 1975). A concentration of highly conductive materials (steel, concrete, grout) creates thermal shorts in locations of the construction details in masonry walls. At present, the impact of the construction details on the overall wall thermal performance is often overlooked. This simplification can lead to errors in predicting the energy efficiency of building envelopes.

Results of the overall wall thermal analysis for uninsulated two-core units, insulated two-core units, cut-web units, uninsulated multicore units, and insulated multicore units are summarized in Figure 5. For all listed wall systems, two densities of concrete were considered during modeling: for two-core and cut-web units, normal density concrete, 120 lb/ft^3 (1,920 kg/m^3) of thermal resistivity 0.19 h·ft^2·°F/Btu per in. (1.32 m·K/W), and for multicore units, lightweight concrete, 40 lb/ft^3 (640 kg/m^3) of thermal resistivity 0.90 h·ft^2·°F/Btu per in. (6.24 m·K/W).

Geometries of wall details were obtained from standard architectural drawings or system manufacturers' design guides. Detailed descriptions of wall details used for computer modeling are presented in Tables 2, 3, and 4.

For all considered wall systems, except an uninsulated two-core unit wall, the R-values of the wall details are 20% to 50% lower than the R-value of the clear wall. For the uninsulated two-core CMU system, the R-value of the clear wall area is so low (1.56 h·ft^2·°F/Btu [0.27 m^2·K/W]) that the thermal performance of the wall details can actually increase the R-value of the overall wall area. In the cut-web unit wall system, two-core units are commonly used for the wall details. For the cut-web unit wall, the R-value of the whole wall is about 12% less than that of the clear wall. For uninsulated multicore units, the clear wall R-value is almost equal to the overall wall R-value. For insulated multicore units, the whole wall R-value is 24% lower than the clear wall R-value. It was observed that for walls made of cut-web or insulated multicore units, R-values of the three most significant wall details (corner, wall/ceiling, and wall/floor details) are 25% to 50% lower than the clear wall R-value. The wall/ceiling detail has the most lowering impact on the overall wall R-value.

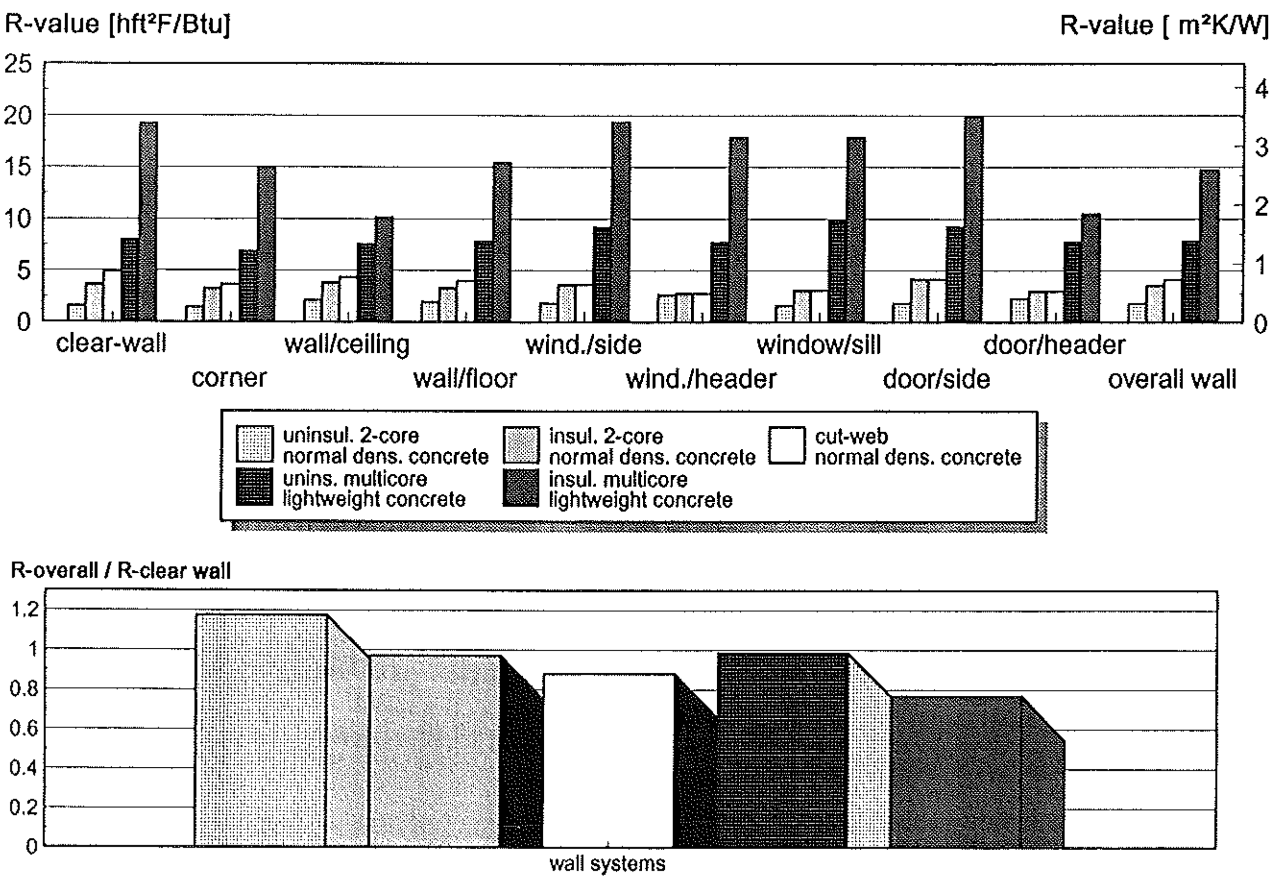


Figure 5 *Overall wall thermal analysis for masonry wall systems.*

TABLE 2 **Wall Details for Uninsulated and Insulated Two-Core Wall Systems**

Wall Detail	Description of Wall Detail	References
Clear wall	Thermal effect of mortar 0.2 h·ft^2·°F/Btu per in. (1.4 m·K/W) and grout 0.11 h·ft^2·°F/Btu per in. (0.77 m·K/W) installed with 16-in. (40-cm.) o.c., included. In case of insulated units: 1-7/8-in. (4.76-cm.) thick EPS inserts.	
Corner	Standard 12-in. (30-cm.) corner units	NCMA 1975, p. 28.
Wall/ceiling	Two courses of blocks with cores filled with grout, 4-in. (10-cm.) wood sill plate, 9-in. (22.5-cm.) joists, R-30 insulation.	Hoke 1988, p. 189,
Wall/floor	Two courses of units with cores filled with grout, 6-in. (15-cm.) joists, plus 8-in. (20-cm.) two-core block with cores filled with grout in case of uninsulated wall, or in case of insulated wall, 6-in. (15-cm.) solid block with 2-in. (5-cm.) thick EPS plate between block and joist.	NCMA 1975, p. 29
Window, door header	2 two-core 6-in. (15-cm.) units, plus 2 steel lintels 3-1/2 × 5 × 1/4-in. (8.9 × 12.5 × 6-cm.)	Hoke 1988, p. 90
Window, door side	Standard two-core units	
Window sill	One row of two-core blocks with cores filled with grout	

TABLE 3 **Wall Details for Uninsulated and Insulated Cut-Web Wall Systems**

Wall Detail	Description of Wall Detail	References
Clear wall	Thermal effect of grout 0.11 h·ft^2·°F/Btu per in. (0.77 m·K/W) installed with 16-in. (40-cm.) o.c., included. Insulated units with 2-1/2-in. (6.4-cm.) thick EPS inserts.	
Corner	Standard 12-in. (30-cm.) two-core units with 2-1/2-in. (6.4-cm.) thick EPS inserts.	IBC 1992, p. 4
Wall/ceiling	One row of U-blocks with cores filled with grout, 2-in. (5-cm.) thick EPS inserts, 4-in. (10-cm.) wood sill plate, 9-in. (22.5-cm.) joists, R-30 insulation.	Hoke 1988, p.189,
Wall/floor	One row of U-blocks with cores filled with grout, 2-in. (5-cm.) thick EPS inserts, 6-in. (15-cm.) joists, 6-in. (15 cm.) solid block with 2-in. (5-cm.) thick EPS plate between block and joist.	NCMA 1975, p. 29
Window, door header	2 two-core 6-in. (15-cm.) units with 2-in. (5-cm.) thick EPS inserts, plus 2 steel lintels 3-1/2 × 5 × 1/4-in. (8.9 × 12.5 × 6-cm.)	Hoke 1988, p. 390
Window, door side	Standard two-core units with 2-in. (5-cm.) thick EPS inserts.	
Window sill	One row of two-core blocks with cores filled with grout	

TABLE 4 **Wall Details for Uninsulated and Insulated Multicore Wall Systems**

Wall Detail	Description of Wall Detail	References
Clear wall	12-in. (30-cm.) multicore units with 3 rows of air cores. In case of insulated units, all cores filled with EPS inserts.	
Corner	12-in. (30-cm.) corner units with one row of air cores.	SII 1991, p. 22
Wall/ceiling	One course of multicore units with two rows of air cores filled with grout, 4-in. (10-cm.) wood sill plate, 9-in. (22.5-cm.) joists, R-30 insulation.	SII 1991, p. 13
Wall/floor	One course of multicore units with two rows of air cores filled with grout, 3/8-in. (1-cm.) concrete pillow, 6-in. (15-cm.) joists, plus 8-in. (20-cm.) multicore block with cores filled with EPS inserts.	SII 1991, p. 14, SII 1989, p. 11
Window, door header	Multicore units 12-in. (30-cm.) with center webs routed to fit steel lintels, 2 steel lintels 3-1/2 × 5 × 1/4-in. (8.9 × 12.5 × 6-cm.)	SII 1991, p. 12
Window, door side	Standard multicore units	
Window sill	Standard multicore units	

CONCLUSIONS

A series of two- and three-dimensional computer simulations was performed to analyze the thermal performance of concrete masonry wall systems. Six shapes of CMUs were considered during finite-difference computer modeling. The analysis of the thermal performance was performed for a wide range of block concrete densities (from normal-density concretes to lightweight concretes). The following conclusions were developed. They may be useful in future thermal design of CMU wall systems.

The thermal efficiency (*TE*) of the insulation material in two-core, cut-web, and multicore units made of normal-density concretes varies between 20% and 40%. This shows that 60% to 80% of the insulation potential does not increase the wall R-value. Application of lightweight concretes in production of masonry units may help to increase the thermal efficiency of the insulation. The *TE* can reach 90% for blocks made of lightweight concrete. Insulation located in multicore units is very ineffective. For normal-density concrete, *TE* is less than 20%; for multicore units made of lightweight concrete, it is from 50% to 60%. It is significant that air cores in units made of normal-density concretes create a very inadequate environment for installing any insulation material. The best solution for these wall systems is probably the use of a rigid foam insulation installed on the surface of the wall. The only exception is the Scandinavian solid unit with the interlocking insulation insert (shape A unit). For this unit, thermal efficiency of the insulation varies from 70% for normal-density concretes to 90% for lightweight concretes. In general, insulation inserts installed in units made of lightweight concretes are much more effective.

The R-values of most CMUs produced from normal-density concretes are very low. The thermal resistance of 12 in. (30 cm) thick uninsulated two-core units made of normal-density concretes is less than 2 $h \cdot ft^2 \cdot °F/Btu$(0.35 $m^2 \cdot K/W$). For the insulated two-core units and uninsulated multicore units, it is less than 4 $h \cdot ft^2 \cdot °F/Btu$ (0.7 $m^2 \cdot K/W$). For insulated multicore and cut-web units, the R-value is less than 7 $h \cdot ft^2 \cdot °F/Btu$ (1.23 $m^2 \cdot K/W$). When the rigid foam insulation cannot be installed (for example, when there is danger of termite damage), the use of lightweight concretes in CMU production is the most effective way to improve their thermal performance. R-values for insulated multicore units and solid units with interlocking insulation inserts (shapes A and B) may reach 20 $h \cdot ft^2 \cdot °F/Btu$ (3.5 $m^2 \cdot K/W$) if they are produced of lightweight concretes—40 lb/ft^3 (640 kg/m^3). The lower thermal conductivity of these concretes reduces thermal bridges across the blocks and improves the total thermal performance of units. Unfortunately, this also reduces the load that can be carried by these walls due to the lower compressive strength. However, some of these units can be used as left-in-place wall forms (in the same way as blocks made of insulating foams) where wall structural integrity is provided by the reinforcement and structural concrete poured into cores.

The mortar joint area usually covers 4% to 10% of the total area of the masonry wall. This generates additional wall heat losses. For two-core units, R-value reduction caused by mortar can reach 12%. Also, in many masonry walls, the R-value is compromised by the highly conductive grout in air cores. Construction of load-bearing walls made of hollow-core blocks often requires installing additional reinforcement and filling air cores with grout. For all CMUs, the grout effect decreases along with the increase of the block concrete thermal resistivity. For two-core, cut-web, and uninsulated multicore units, the grout effect decreases the clear wall R-value by 3% to 12%. In the case of insulated multicore units, where grout fillings simply replace insulation inserts, R-value reduction may reach 30% for normal-density concretes and 25% for lightweight concretes.

Building wall systems are a combination of the clear wall area and wall details. They cannot be accurately characterized simply by studying the clear wall area. For the wall systems reported in this study, as much as 25% of the overall wall area was different in construction and thermal performance than the clear wall area. For wall units with insulating inserts, R-values of most of the wall details were 20% to 50% lower than that of the clear wall. A fairly straightforward building elevation was used for this modeling (wall openings represent only 13% of the floor area). In most residential buildings, the wall area distribution has a smaller percentage of the clear wall area because the contribution of the area of wall openings' details in the overall wall area is much higher. In many residential buildings, fenestration represents 20% to 30% of the floor area. If thermal performance of wall details is not incorporated in R-value calculations, significant errors may appear in determining the energy efficiency of the building envelope. For well-insulated masonry wall systems such as insulated multicore units, errors can reach 25% of the clear wall R-value. In addition, current techniques de-emphasize creative energy-efficient design of the wall system details because envelope system designers cannot claim performance benefits due to innovative detailing.

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