

Arranging Insulation for Better Thermal Resistance in Concrete and Masonry Wall Systems

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SUMMARY:

This paper investigates how the spatial arrangement of thermal insulation influences the overall thermal resistance of concrete and masonry wall systems. Multi-dimensional finite difference modeling was used for this purpose. Concrete masonry units (CMUs) are commercially produced in various geometries and with different weight concretes. Although insulation inserts can increase a CMUs thermal performance, thermal bridging through the solid webbing of the CMUs can greatly reduce the effectiveness of the integrated insulation. Different commercially available CMU geometries and concrete weights were investigated using finite difference modeling to show the impact on overall CMU R-value and to determine the thermal efficiency of the insulation inserts.

1. Introduction

A wide variety of concrete and masonry systems exists on the market today for residential and commercial buildings. Systems vary in material configuration and type of concrete, and both influence the extent of thermal bridging. Insulation can add significant cost to a masonry unit, so it is critical to ask: “To what extent does the insulation improve the R-value?” and “To what extent does thermal bridging compromise insulation integrity?” Using higher density concrete improves a CMU’s strength but can diminish its thermal performance. Understanding these issues allows designers to use materials efficiently, and provide best thermal performance at a reasonable cost.

Thermal bridges in building envelopes occur mostly in places where structural and insulating materials have differing thermal conductivities. Concrete and masonry technologies can contain complex configurations of thermal insulation (Kosny et al. 1998). For most CMUs made of normal-weight concrete of density between 1,920-2,240 kg/m³, the thermal conductivity of concrete can be 20 times higher than that of foam insulation. For some shapes of insulation and structural components, hidden thermal shorts may cause considerable heat losses, making it critical to optimize the sequence of layers, density of concrete, and configuration of mass and thermal insulation in building envelopes.

Steady-state and dynamic heat transfer modeling techniques have been in use for many years, and many commercial software packages can be used to perform these analyses. Sometimes, however, non-conventional analytical and experimental methods must be developed to better understand massive building envelope assembly performance. During the second half of the twentieth century dynamic hot-box testing was introduced to experimentally determine the transient thermal characteristics of complex massive systems (Kasuda 1969; Brown and Stephenson 1993; Kosny et al. 1998). Equivalent wall theory was introduced in order to enable numerical analysis of complex wall assemblies using one-dimensional thermal models (Kossecka and Kosny 1996; Kossecka 1999;

Kosny et al. 2001). Several energy codes, including Model Energy Code 1995, ASHRAE Standard 90.2, and IECC 2006, have already started to incorporate some energy performance data for massive wall configurations (CABO 1995, ASHARE 1993, ICC 2006).

Typically, wall R-value measurements are carried out by the hot-box apparatus such as the one described in ASTM C1363 (2005). The best-known historical hot-box test data for concrete and masonry walls can be found in (Valore 1988; Van Geem 1986; and James 1990) and in the ORNL wall material database (Kosny and Christian 1993). This paper analyzes detailed R-value simulations performed for several types of commercially available CMUs. Structural optimizations were not performed.

2. Steady State Thermal Performance of Concrete Masonry Units

Concrete masonry units (CMUs) are available in a variety of configurations. Some are simple and consist of only a single material, while others have interlocking paths of structural and insulating materials. In this paper we investigate simple two-core hollow block CMUs, common in the U.S., and more advanced multicore and interlocked CMUs, common in Europe. Steady-state simulations were used to analyze heat flow through walls made of different types of CMUs. The finite difference program, HEATING-7.3 (ORNL) used in this study was validated against the hot-box results from masonry and frame systems (Kosny and Syed 2004).

Six types of 12 in. (300 mm) thick CMUs – FIG 1 – were studied, including solid-block, two-core hollow block, cut-web block, multicore block, solid block with interlocking insert, and solid block with serpentine insulation insert; dimensions are given in Table 1.

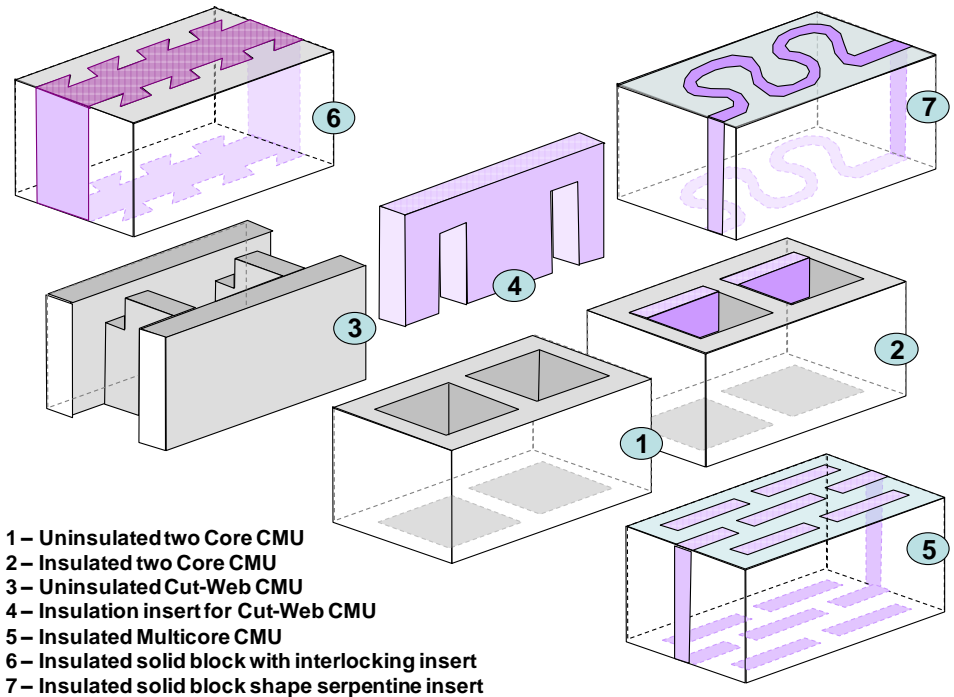


FIG 1. Schematics of six types of CMUs used in thermal performance analysis.

TABLE 1. Dimensions for analyzed 12 x 16 x 8 in. (300 x 400 x 200 mm) CMUs. Units: in. (mm).

CMU type	Side walls		Concrete webs		Insulation insert		Web height reduction	
two core	1.75	(44.5)	1.75	(44.5)	1.88	(47.8)	-	
cut-web	1.75	(44.5)	2.00	(51.0)	2.50	(63.5)	3.00	(76.0)
multicore	1.50	(38.0)	1.50	(38.0)	2.00	(51.0)	-	
solid CMU with serpentine insulation	2.00	(51.0)	2.50	(63.5)	1.70	(43.2)	-	
solid CMU with interlocking insulation	4.00	(102.0)	1 in. tongue & groove		2.00	(51.0)	-	

Understanding the tradeoff between CMU strength and thermal bridging is important. Higher density concrete tends to have more compressive strength than lightweight concrete, but lightweight concrete has a higher thermal resistivity. Solid CMUs are normally produced with lightweight concretes. The R-value for a solid 12 in. (300 mm) thick CMU made of lightweight concrete ranges from 0.8-1.7 m²·K/W.

Using 3D finite difference calculations, the R-value was computed as a function of concrete resistivity for all six types of CMUs, some both with and without insulation, according to winter boundary conditions defined in ASHRAE (2009 Ch.26, Table 1). All cases were simulated for 12 in. (300mm) thick CMUs. All insulation inserts were assumed to have the same thermal resistivity of 27.7 m·K/W. Thermal resistances for each CMU were calculated for five different values of concrete thermal resistivity: 1.32, 1.94, 2.77, 4.09, 5.96 m·K/W). These values approximately correspond, respectively to the following densities of concrete: 1,920; 1,600; 1,280; 980; and 640 kg/m³ (ASHRAE 1993). The relationship between concrete density and thermal resistivity is shown in FIG 2 for various types of concrete. Note that foam insulation inserts have a thermal resistivity of about 28 m·K/W, which is 4 to 14 times higher than lightweight concretes and up to 60 times higher than normal weight concretes.

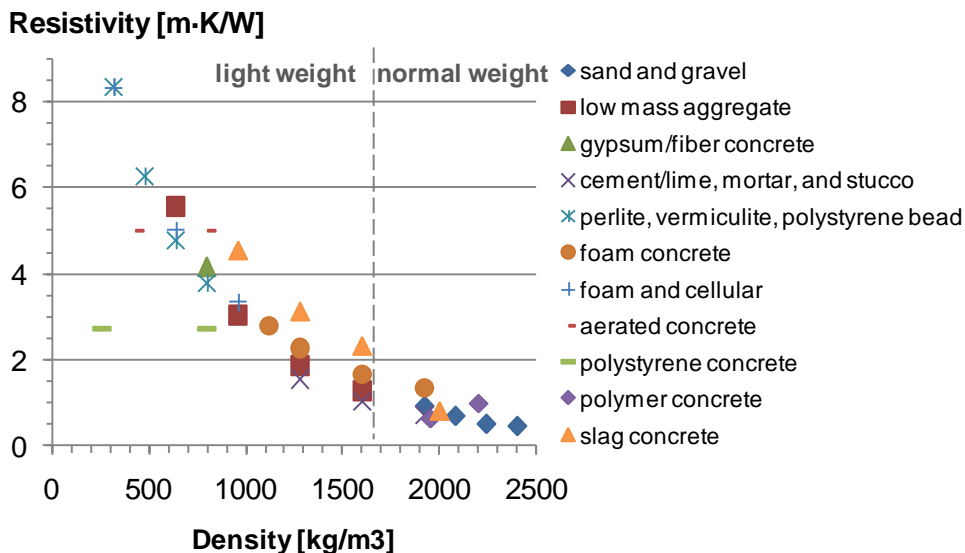


FIG 2. Concrete thermal resistivity vs. density (ASHRAE 2009). Foam insulation inserts are far more resistive at about 28 m·K/W.

As shown in FIG 3, the thermal performance of two-core units made of normal density concretes is very low; for an uninsulated 12 in. (300 mm) thick unit, the R-value is below $0.35 \text{ m}^2\cdot\text{K}/\text{W}$. For insulated units made of normal density concrete, the R-value remains well below $0.62 \text{ m}^2\cdot\text{K}/\text{W}$. Since foam inserts are located in air cavities portioned by highly conductive concrete webs, they cannot notably reduce negative effects of thermal shorts generated by the transverse webs. If two-core units are made of lightweight concretes (not a common practice in the U.S.), their R-values may be higher: about $0.7 \text{ m}^2\cdot\text{K}/\text{W}$ for uninsulated CMUs, and $1.4 \text{ m}^2\cdot\text{K}/\text{W}$ for insulated units.

Cut-web CMUs were designed to reduced heat losses caused by transverse concrete webs in two-core units. FIG 3 shows that the increase in thermal resistance caused by 40% concrete web reduction is minimal for units made of normal density concretes: a comparison of R-value between insulated two-core and cut-web units shows less than $R-0.35 \text{ m}^2\cdot\text{K}/\text{W}$ difference. For the insulated 12 in. thick cut-web unit made of normal density concrete, the R-value is below $0.95 \text{ m}^2\cdot\text{K}/\text{W}$. R-values of the cut-web units made of lightweight concrete could exceed $R-1.94 \text{ m}^2\cdot\text{K}/\text{W}$.

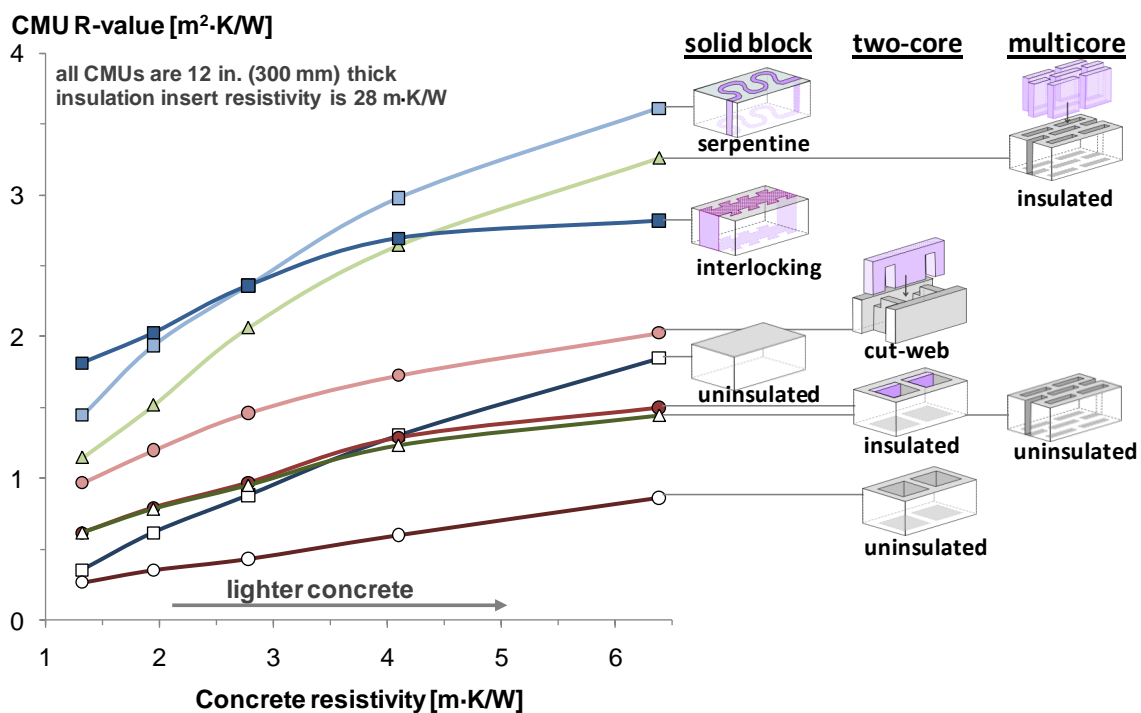


FIG 3. Simulated R-values of concrete masonry units with different insulation configurations and the dependence on the concrete R-value. Normal weight concrete is represented by the two left-most shape markers.

As shown in FIG 3, for multicore units made of normal density concretes, the R-value of an uninsulated 12 in. (300 mm) thick unit is below $0.62 \text{ m}^2\cdot\text{K}/\text{W}$ and for an insulated unit it is about $1.2 \text{ m}^2\cdot\text{K}/\text{W}$. It is interesting that the R-value of the uninsulated multicore units is about equal to that of the insulated two-core unit. For insulated multicore units made of lightweight concrete, the R-value could exceed $3.35 \text{ m}^2\cdot\text{K}/\text{W}$.

Solid blocks with interlocking insulation inserts are usually made of lightweight concretes. As shown in FIG 3, for solid units with integral insulation inserts, the R-value can exceed $2.82 \text{ m}^2\cdot\text{K}/\text{W}$. For units with serpentine foam insulation, R-value can reach $3.52 \text{ m}^2\cdot\text{K}/\text{W}$.

Note that all R-values presented above account only for the blocks themselves and do not account for mortar or grout. The mortar joint area usually covers 4-10% of the total wall area. These joints may generate additional wall heat losses in masonry walls. FIG 4 shows a detailed computer model of three uninsulated two-core CMUs connected together with mortar joints. The areas where isotherms are not perpendicular to the direction of bulk heat flow indicate intense thermal bridging. In the case of two-core CMUs made of normal density concrete, the mortar effect is negligible since thermal conductivities of mortar and block concrete are almost the same. In the case of lightweight concrete, the thermal effect of mortar is more significant – the R-value reduction can exceed 12% for two-core units.

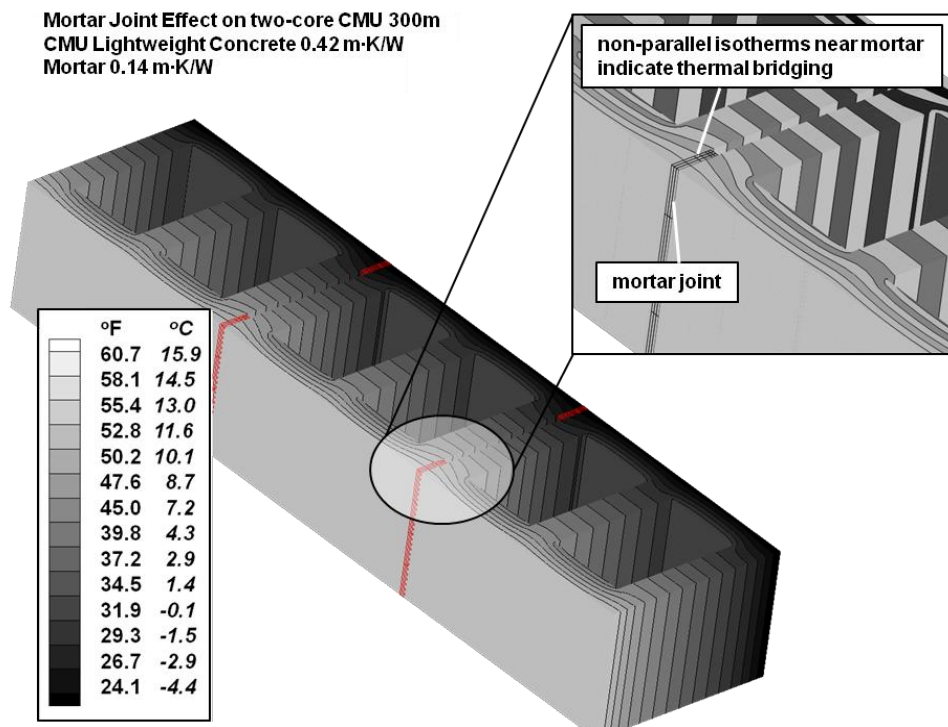


FIG 4. Effect of mortar on thermal bridging heat flow.

3. Insulation Thermal Efficiency

Foam insulation inserts add significant cost to CMUs, so using insulation effectively is important. There are many types and shapes of interstitial insulation inserts. By studying the relative thermal efficiency TE of insulation materials within CMUs, one can learn how to design highly insulating CMUs that use less insulation material. This can help to optimize concrete and masonry system cost.

When the nominal R-value of used insulation is compared to the increase of wall R-value caused by this insulation, the actual increase of the wall R-value is often significantly lower (Kosny and Christian 1993; Kosny and Syed 2004). Unintended thermal bridges can produce significant heat losses, resulting in ineffective usage of the insulation material.

The method of estimating TE value is based on R-value comparison of insulated (R_i) and uninsulated (R_u) masonry 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 A_f (m^2) as the CMU under consideration, and containing the same volume V_{ins} (m^3) which is used to insulate this CMU. TE may be expressed by the following equation:

$$TE = \frac{R_i - R_u}{R_e} \times 100\% \quad (1)$$

Where R_i R-value of insulated CMU,
 R_u R-value of uninsulated CMU, and
 R_e R-value of insulation material alone, configured in one uninterrupted layer.

To calculate equivalent thickness d_e of thermal insulation used in CMU, the insulation volume V_{ins} is divided by the face surface area A_f of the CMU. Equivalent thickness d_e (m) can be expressed as follows:

$$d_e = \frac{V_{ins}}{A_f} \quad (2)$$

Equivalent R-value of the consumed insulation material R_e is:

$$R_e = r_i \times d_e \quad (3)$$

where r_i is the thermal resistivity of the insulation material.

The TE of the insulation material depends on the CMU shape and concrete R-Value, as shown in FIG 5. For all CMUs, the insulation was more effective for lightweight concrete than for normal weight concrete, and in some cases more than twice as high. For most insulated blocks made of lightweight concrete (except insulated multicore CMUs), the TE can reach 60-90%. Solid block CMUs with interlocking insulation had the highest effectiveness, ranging from about 70-90%. The serpentine-insulated solid block CMU and both insulated two-core CMUs showed medium effectiveness ranging from about 30-80%. Multicore CMU insulation was very ineffective ranging from only 20-60%. Filling multiple discontinuous air cavities with insulation is less effective because the air cavities provide a moderate base insulating value.

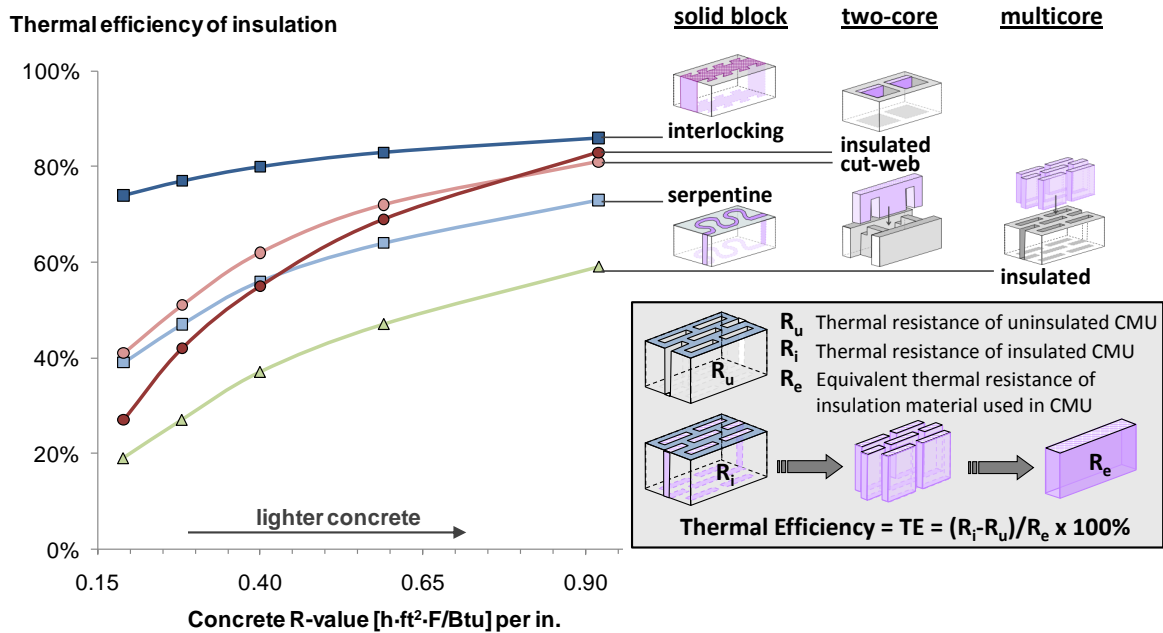


FIG 5. Thermal efficiency of insulation in CMUs as a function of concrete thermal resistivity.

Next, a slightly different method of comparison is presented, where the insulated CMU is compared with a CMU made of the same volume of insulation and concrete, but arranged differently so that the

concrete and insulation are each continuous layers arranged in series. In this way, the nominal case has no thermal bridges and is a useful benchmark by which to gauge insulating performance. From FIG 6, it is evident that the interlocking CMU performs close to the ideal nominal case, the two-core and cut-web CMUs perform moderately well, while the serpentine and multicore CMUs again are seen to use insulation less effectively.

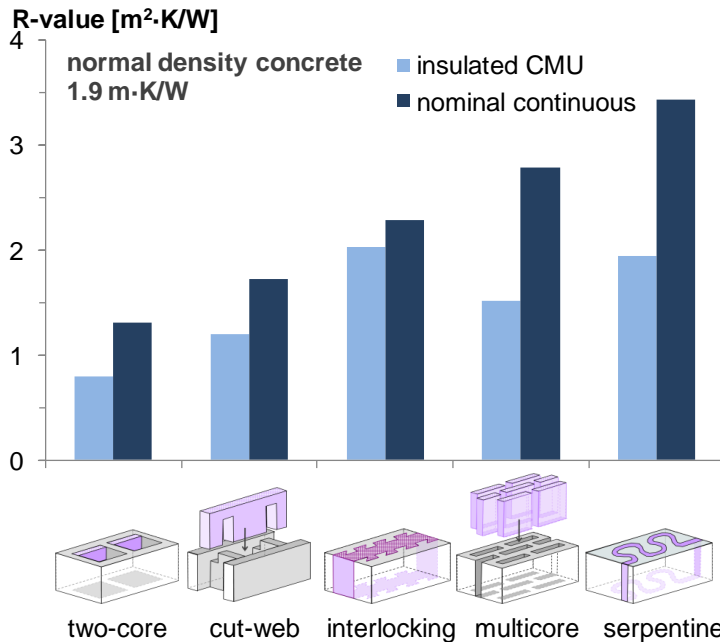


FIG 6. Comparison of insulated CMU R-value and nominal R-value. Nominal R-value is that obtained if insulation and concrete were two separate layers and all air gaps removed.

4. Conclusions

In this study a finite difference computer modeling was utilized to analyze the thermal performance of concrete masonry wall systems. Six basic CMU shapes were considered. The analysis of the thermal performance was performed for a wide range of concrete densities (from normal density concretes to lightweight concretes). The following series of conclusions were developed which may be useful in the future thermal designing of concrete and masonry wall systems:

The R-values of most CMUs produced in Northern America from normal density concretes are very low. The thermal resistance of 12 in. (300 mm) thick uninsulated two-core units made of normal density concretes is below $0.35 \text{ m}^2\cdot\text{K}/\text{W}$. For the insulated two-core units, and uninsulated European multicore units, it is less than $0.70 \text{ m}^2\cdot\text{K}/\text{W}$. For insulated multicore and cut-web units R-value is below $1.23 \text{ m}^2\cdot\text{K}/\text{W}$. The mortar joint area usually covers 4 to 10% of total masonry wall area, and creates additional wall heat losses. For two-core units, R-value reduction caused by mortar can reach 12%.

The use of lightweight concretes in production of CMUs is one of the most effective ways to improve their thermal performance. More complex CMUs made of lightweight concretes and containing interlocking or serpentine foam inserts may have R-values ranging between 2.82 and $3.52 \text{ m}^2\cdot\text{K}/\text{W}$. The thermal efficiency TE of the insulation material in two-core, cut-web, and multicore units made of normal density concretes varies only between 20 and 40%. This shows that 60 to 80% of the used thermal insulation does not generate any increase of the wall R-value, indicating poor use of insulation material. The results of this study show that an application of lightweight concretes in production of masonry units may help in increasing insulation TE , which can reach 90% for blocks made of lightweight concretes.

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