[T01-91] Energy Performance of Concrete Buildings in Five Climates

Martha G. VanGeem[1,*], Medgar L. Marceau[2]

[1]Principal Engineer, Building Science and Sustainability, CTLGroup, 5400 Old Orchard Road, Skokie, Illinois, 60077-1030 USA (847) 972-3156
[2]Building Science Engineer, Building Science and Sustainability, CTLGroup, 5400 Old Orchard Road, Skokie, Illinois, 60077-1030 USA (847) 972-3154

Corresponding email: mvangeem@CTLGroup.com

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SUMMARY

This paper provides information on energy savings in mid-rise commercial buildings due to additional thermal mass and for exceeding ASHRAE 90.1-2004 thermal performance requirements in the building envelope. The results also indicate the points available for optimizing energy performance under the Energy and Atmosphere (EA) credit of LEED-NC.

Five-story prototype buildings with plan dimensions of 32 by 32 m and a window-to-wall ratio of 0.40 have been modeled using the software program VisualDOE. The buildings were modeled in six cities representing the range of climates in the US. A table is included showing how results for five climates relate to similar climates in other major cities worldwide. The buildings include: precast concrete walls, curtain walls, and exterior insulation finishing system (EIFS) walls with either structural steel or reinforced concrete frame.

The energy modeling shows that the effect of thermal mass in concrete framed buildings, combined with thermal improvements to the building envelopes (including walls and windows), results in energy savings up to 23% relative to the baseline steel framed EIFS buildings. This energy savings qualifies for up to four LEED-NC v2.2 points.

INTRODUCTION

This paper provides information on energy savings in mid-rise commercial buildings due to additional thermal mass and for exceeding American Society of Heating, Refrigerating and Air Conditioning Engineers, *ASHRAE Standard 90.1-2004 (*ASHRAE 2004) thermal performance requirements in the building envelope. The results also indicate the points available for optimizing energy performance under the Energy and Atmosphere (EA) credit of version 2.2 of LEED for New Construction and Major Renovation (LEED-NC) (USGBC 2005). Obtaining points for this EA credit using the performance path requires modeling with whole-building energy simulation software; and modeling the effect of thermal mass requires software that models yearly energy use on an hourly basis (USGBC 2005, ASHRAE 2004). To accurately simulate buildings with materials that have time-dependent properties (such as the heat capacity of concrete) in a dynamic temperature environment (such as outdoor air temperatures), software with time-dependent capabilities is required. Materials such as concrete, masonry, and stone have a beneficial effect on a building's thermal environment because they moderate and delay extreme changes in temperature resulting in lower energy use. This complex behavior is often simply called thermal mass effect.

The LEED-NC (USGBC 2005) green building rating system is one of a family of voluntary rating systems for designing, constructing, operating, and certifying green buildings. All of the LEED rating systems are point-based systems. Points are awarded for meeting certain requirements, such as energy conservation and using recycled-content materials. The LEED-NC Credit EA 1 for optimizing energy performance can provide up to 10 points for energy cost savings beyond *ASHRAE Standard 90.1-2004*. A building's thermal mass, such as the thermal mass of concrete walls and concrete structural elements, helps obtain these points.

METHODOLOGY

Climates

Since thermal mass effects vary with climate, the buildings were modeled in six cities representing the range of climates in the US. Five of these cities are representative cities for the U.S. Department of Energy's climate zones in *ASHRAE 90.1- 2004*. The cities and the climate zone (CZ) numbers are:

- Miami, Florida—a very hot and humid climate (CZ 1)
- Phoenix, Arizona—a hot and dry climate with large daily temperature swings (CZ 2)
- Memphis, Tennessee—a warm climate (CZ 3)
- Salem, Oregon—a mixed climate (CZ 4)
- Denver, Colorado—a cold climate with large daily temperature swings (CZ 5)
- Chicago, Illinois—a cold climate (CZ 5)

Table 1 presents climates zones for other major cities worldwide so that results of this paper can be compared to other locations. Although no cities were simulated for climate zones 6, 7, and 8 (the coldest climates), most of the world's population resides in climate zones 1 through 5. Energy costs are based on the costs in the U.S. cities above. Actual energy costs will vary depending on location.

Simulation tool

The results are based on modeling a typical five-story commercial buildings using the whole-building energy simulation software VisualDOE 4.0 (AEC 2004). The modeling conforms to the requirements of Appendix G: Performance Rating Method in *ASHRAE 90.1-2004*. The basis for calculating points in EA Credit 1 is the energy cost of a baseline building. The building performance rating method in Appendix G is intended for rating the energy efficiency of a building whose design exceeds the requirements of the standard. In this method, two buildings are modeled with energy simulation software: a baseline building that meets the standard and the proposed above-standard building. The energy costs of two buildings are compared to determine the percent improvement of the proposed building. Appendix G prescribes that the baseline building be a lightweight steel framed building. The baseline building consists of an exterior insulation finishing system (EIFS) with steel stud walls, structural steel frame, and metal deck floors with concrete topping slab.

Building description

This section describes the features that are common to all the buildings and the features that differ because of climate or modeling scenario (Marceau and VanGeem 2007).

Table 1. Climate zones for major world cities (ASHRAE 2004)

Climate Zone 1 (very hot), Simulated City: Miami, Florida, USA	
Bahamas, Nassau	Mexico, Guadalajara
Brazil, Rio de Janeiro	Pakistan, Karachi
India, Mumbai	Saudi Arabia, Riyadh
India, Delhi	Singapore, Singapore
Indonesia, Djakarta	Thailand, Bangkok
Jamaica, Kingston	Venezuela, Caracas
Malaysia, Kuala Lumpur	Vietnam, Saigon
Climate Zone 2 (hot), Simulated City: Phoenix, Arizona, USA	
China, Hong Kong	Peru, Lima
Egypt, Cairo	Taiwan, Taipei
Climate Zone 3 (warm), Simulated City: Memphis, Tennessee, USA	
Argentina, Buenos Aires	Japan, Tokyo
Australia, Sydney	Kenya, Nairobi
China, Shanghai	Mexico, Mexico City
Israel, Jerusalem	Syria, Damascus
Climate Zone 4 (mixed), Simulated City: Salem, Oregon, USA	
Chile, Santiago	Korea, Seoul
China, Beijing	South Africa, Cape Town
France, Paris	Turkey, Istanbul
Italy, Rome	United Kingdom, London
Climate Zone 5 (cold), Simulated Cities: Chicago, Illinois and Denver, Colorado, USA	
Belgium, Brussels	Hungary, Budapest
Canada, Vancouver	Ireland, Dublin
China, Dalian	Netherlands, Amsterdam
Czech Republic, Prague	Switzerland, Zurich
Germany, Berlin	Tibet, Lhasa
Climate Zone 6 (colder), Simulated City: None	
Canada, Nova Scotia, Halifax	Norway, Oslo
Canada, Ontario, Toronto	Russia, Moscow
Canada, Quebec, Montreal	Sweden, Stockholm
Climate Zone 7 (very cold), Simulated City: None	
Canada, Calgary	Finland, Helsinki
China, Haerbin	Iceland, Reykjavik
Climate Zone 8 (subartic), Simulated City: None	
Canada, Northwest Territories, Yellowknife	

All the buildings in this study are five-story commercial buildings with plan dimensions 32.0 by 32.0 m. They are square in plan with the same amount of glazing equally distributed on each wall to minimize the effect of building orientation (whether the building faces north, south, east, or west). The building height, 19.2 m, is based on 4.6 m for the first story and 3.7 m for the remaining four stories. The ground-level floor consists of a 150 mm cast-in-place concrete slab-on-ground. Each floor is modeled with five zones: four perimeter zones and one central zone. The depth of the perimeter zones is 10.7 m. The center zone is 10.7 by 10.7 m. Each façade of each story has a strip of ten windows each measuring approximately 1.5 m high by 3.2 m wide. Windows are flush-mounted (non-recessed) and are equally spaced. Windows are non-operable and have no blinds or shading devices. The overall window to wall ratio is 0.40. No exterior shading was assumed around the buildings. This assumption is typical for new construction in rural and suburban locations.

Walls

Buildings are the same except for the wall construction, the structural frame, the location of the internal loads, and the insulation and fenestration required to meet the standard. Table 2 summarizes the structural variations. A system of abbreviated names is used to simplify the discussion of the modeled scenarios. The first letter in the abbreviated name refers to the exterior wall system: “E” for exterior insulation and finish systems (EIFS), “C” for curtain wall, and “M” for precast concrete (the letter M is used because of the thermal mass effects of concrete). The second letter refers to the structural framing system and interior walls and floors: “L” for light and “M” for mass. The light materials are structural steel framing and metal deck floors with concrete topping slab. The mass materials are reinforced concrete framing and concrete floors. An “X” indicates that the building envelope exceeds the energy standard requirements and an “I” indicates that the internal loads are clustered near the central core of the building.

Table 2. Buildings modeled

Designation	**Exterior walls**	**Structural frame**	**Floors**	**Interior walls**
EL (baseline)	EIFS & metal stud	structural steel	concrete/metal deck	metal stud
CL	curtain wall	structural steel	concrete/metal deck	metal stud
ML	Precast concrete	structural steel	concrete/metal deck	metal stud
EM	EIFS & metal stud	concrete	concrete	concrete
CM	curtain wall	concrete	concrete	concrete
MM	Precast concrete	concrete	concrete	concrete
MLX	Precast concrete exceeding standard	structural steel	concrete/metal deck	metal stud
MMX	Precast concrete exceeding standard	concrete	concrete	concrete
MMI	precast concrete	concrete	concrete	concrete
MMXI	precast concrete exceeding standard	concrete	concrete	concrete

Buildings EM, CM, and MM are like EL, CL, and ML, respectively, except they have more concrete in interior floors and walls. Buildings MLX and MMX are like ML and MM, respectively, except their building envelopes exceed the standard. Buildings MMI and MMXI are like MM and MMX, respectively, except that internal loads are clustered near the central core of the building, where most of the interior concrete is located.

The amount of insulation in the exterior walls was varied to meet the requirements of *ASHRAE 90.1-2004*. Table 3 shows the minimum requirements for EIFS and curtain walls along with the construction of the walls selected to meet the standard. Table 4 shows the minimum requirements for concrete walls, the insulation selected to meet the standard, and the insulation selected to exceed the requirements. The thermal performance requirements for fenestration are shown in Table 5 along with the properties of the windows selected to meet the standard. Table 6 shows the properties of the selected windows that were used to exceed the requirements.

Roofs

The roofs on all buildings in this study consist of ⅝-in. (16-mm) gypsum wallboard, open-web steel joists, ribbed steel deck, board insulation, and built-up waterproofing membrane.

Table 3. Requirements in ASHRAE 90.1-2004 for EIFS and curtain walls

Location	**Maximum required U-factor***	**Insulation and resulting wall U-factor to meet the standard**	
		Insulation**	**U-factor***
Miami (CZ 1)	0.704	RSI-2.3 batts	0.704
Phoenix (CZ 2)	0.704	RSI-2.3 batts	0.704
Memphis (CZ	0.704	RSI-2.3 batts	0.704
Salem (CZ 4)	0.704	RSI-2.3 batts	0.704
Denver (CZ 5)	0.477	RSI-2.3 batts + RSI-0.7 boards	0.477
Chicago (CZ 5)	0.477	RSI-2.3 batts + RSI-0.7 boards	0.477

**These U-factors, in units of W/m^2·K, include the thermal bridging effects of steel stud framing and the thermal resistance of inside and outside air films.*

***Batt insulation is installed between steel studs, which are 40 cm on-center. Board insulation is continuous over the steel studs.*

Table 4. Requirements in ASHRAE 90.1-2004 for concrete walls

Location	**Maximum required U-factor***	**Insulation and resulting wall U-factor to meet the standard**	
		Insulation**	**U-factor***
Miami (CZ 1)	3.293	None	2.300
Phoenix (CZ 2)	3.293	None	2.300
Memphis (CZ 3)	0.857	RSI-2.3 batts	0.738
Salem (CZ 4)	0.857	RSI-2.3 batts	0.738
Denver (CZ 5)	0.698	RSI-2.6 batts w/ 13 mm air space	0.642
Chicago (CZ 5)	0.698	RSI-2.6 batts w/ 13 mm air space	0.642
All Exceeding Code	Not applicable	RSI-2.3 batts + RSI-0.7 boards	0.486

**These U-factors, in units of W/m^2·K, include the thermal bridging effects of steel stud framing and thermal resistance of inside and outside air films.*

***Batt insulation is installed between steel studs, which are 400 mm on-center. Board insulation is continuous over the steel studs.*

Table 5. Fenestration requirements in ASHRAE standard 90.1-2004

Location	**Required**		**Selected windows**			
	Max. U-factor*	**Max. SHGC****	**U-factor***	**SHGC†**	**VLT††**	**VisualDOE identifier & name**
Miami (CZ 1), Phoenix (CZ 2)	6.93	0.25	5.00	0.25	0.13	1411 Single clear LR13
Memphis (CZ 3)	3.24	0.25	2.95	0.23	0.18	2420 Double Ref-B Clear-L Air
Salem (CZ 4), Denver (CZ 5), Chicago (CZ 5)	3.24	0.39	2.95	0.30	0.27	2426 Double Ref-B Clear-H Air

**U-factor in units of W/m^2·K. **Solar heat gain coefficient (SHGC) requirement in a non-north orientation. †Solar heat gain coefficient at a 60° angle of incidence. ††Visible light transmittance (VLT) is not a requirement.*

The standard requires a U-factor no more than 0.358 W/m^2·K including air films. The thermal performance requirements for roofs are met using RSI-2.6 board insulation in all locations. The resulting roof U-factor is 0.352 W/m^2·K including air films. For Miami (CZ 1) and Phoenix (CZ 2), the roofs exceeding requirements have RSI-2.6 board insulation. For Memphis (CZ 3), Salem (CZ 4), Denver (CZ 5), and Chicago (CZ 5), the roofs exceeding requirements have RSI-3.5 board insulation. The built-up roof is medium-colored and has a coefficient of solar absorptance of 0.70 (this is the default value required in Appendix G).

Table 6. Selected Windows that Exceed Requirements in ASHRAE Standard 90.1-2004

Location	U-factor*	SHGC	VLT	VisualDOE identifier & name
Miami (CZ 1), Phoenix (CZ 2)	2.95	0.23	0.18	2406 Double ref A clear-H IG
Memphis (CZ 3), Salem (CZ 4), Denver (CZ 5), Chicago (CZ 5)	1.76	0.15	0.14	2823 Double Electrochromic Ref Bleached/Colored, 12.7-mm Gap

**U-factor in units of* $W/m^2{\cdot}K$.

RESULTS AND DISCUSSION

The energy modeling using VisualDOE 4.0 (AEC 2004) shows that thermal mass in concrete buildings lowers both energy *use* and *cost* relative to the baseline steel framed EIFS building. Results are shown in Figure 1. For each location, the figure shows yearly energy use and cost. Energy use includes heating, cooling, pumps, fans, domestic hot water, lighting, and receptacle loads. Detailed results are presented in Marceau and VanGeem (2007).

Energy cost savings

In most scenarios, the effect of a concrete frame with or without precast concrete walls is to lower energy *use* and energy *cost* relative to the baseline building (steel frame EIFS, EL). In Memphis (CZ 3), Salem (CZ 4), Denver (CZ 5), and Chicago (CZ 5), energy cost savings of 6 to 11% are indicated for the three concrete frame buildings meeting the standard compared to the baseline building (compare EM, CM, and MM to EL in Figure 1). In Miami (CZ 1) and Phoenix (CZ 2), the variations in energy cost scenarios are small. The additional thermal mass in the frame saves some energy costs (less than 5%: compare CL to CM, EL to EM, and ML to MM in Figure 1), but the buildings with concrete walls have 1 to 7% greater energy costs than the baseline building (compare ML and MM to EL in Figure 1).

Energy cost savings due to walls

Due to thermal mass effects, *ASHRAE 90.1-2004* does not require mass walls to have as high an R-value as low-mass walls. Comparing buildings with the same structural frame but different walls shows small differences in energy costs savings (compare EL to CL to ML and compare EM to CM to MM in Figure 1). Energy cost savings range from -6% to 3% and the average is 1%. These results indicate that the reduced R-values for mass walls allowed in energy codes and standards are justified.

For a given structural frame, the EIFS and curtain wall buildings in Miami (CZ 1) and Phoenix (CZ 2) use 3 to 6% less energy than the buildings with uninsulated concrete walls(compare EL and CL to ML, and compare EM and CM to MM in Figure 1). According to the minimum standard requirements, concrete walls in Miami (CZ 1) and Phoenix (CZ 2) do not require added insulation, but EIFS and curtain walls in these same cities require at least R-13 batt insulation. Therefore, the mass walls in these climates are more than three times more conductive than the lightweight walls yet use about the same amount of energy due to their thermal mass.

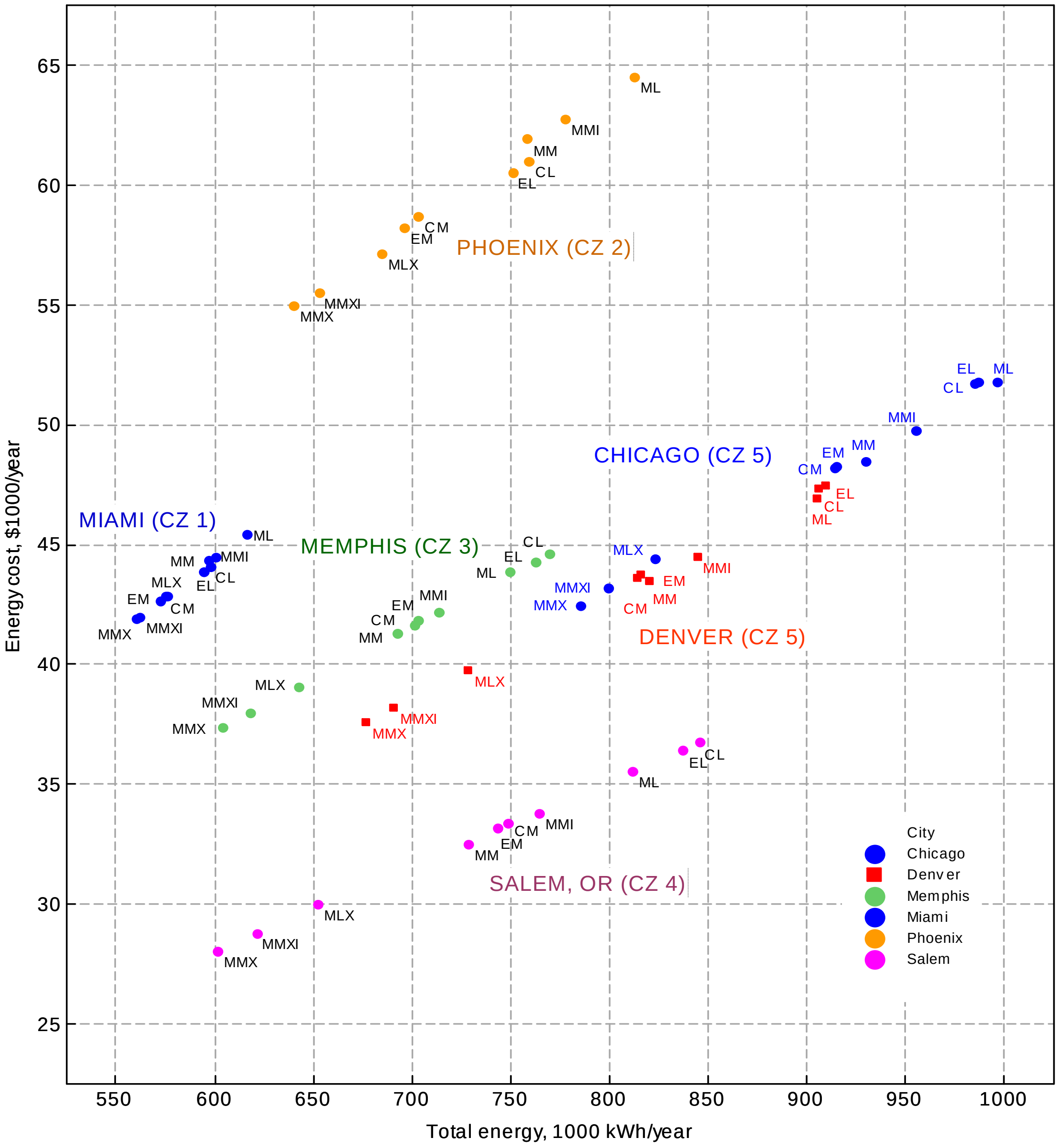

Figure 1. The relationship between annual energy use and cost varies by city.

Walls exceeding energy standard requirements

Results shows significant energy cost savings for building envelopes (including walls and windows) exceeding the standard. The amount of added insulation chosen to make the concrete walls exceed the standard is not unusual; it is about the same as the amount of insulation in the EIFS and curtains walls meeting the standard in Denver (CZ 5) and Chicago (CZ 5). Even more insulation could have been used, but using a low value shows how even modest improvements can result in significant energy savings. This shows that the amount of added insulation is realistic and that concrete with insulation saves energy. Energy cost savings are in the range of 9 to 23% for all cities except Miami (CZ 1) where the energy cost savings are about 5% (compare MMX to EL in Figure 1).

LEED EA Credit 1.

In the four cities representing warm, mixed, and cold climates, reinforced concrete frame buildings with building envelopes that exceed the standard will most likely qualify for points under LEED-NC EA Credit 1. In the cold climate category (Denver [CZ 5] and Chicago [CZ 5]), these buildings will likely qualify for 3 points, that is, at least 17.5% energy cost savings (actual is Denver [CZ 5] 21% and Chicago [CZ 5] 18%). In the mixed climate category (Salem [CZ 4]), these buildings will likely qualify for 4 points, that is, at least 21% energy cost savings (actual is 23%). In warm climates, such as Memphis (CZ 3), these buildings will likely qualify for 2 points, that is, at least 14% energy cost savings (actual is 16%). Note that adding insulation to uninsulated concrete walls in hot and very hot climates (Miami [CZ 1] and Phoenix [CZ 2]) does *not* save enough energy to gain points (energy savings must be 10.5% or greater). In addition, the steel frame buildings with concrete walls and windows exceeding the standard will likely qualify for 2 points, at least 14% energy savings, in Salem (CZ 4) (actual is 17%) and Denver (CZ 5) (actual is 16%). These results are particularly significant because the buildings have a relatively large window area (0.4 window-to-wall ratio) and very large associated energy loads.

Results are for the buildings modeled in the stated cities. Actual energy use and cost will vary depending on climate, building type and occupancy, orientation, actual building materials, and fenestration amount and type.

CONCLUSION

The energy modeling using VisualDOE 4.0 shows that the effect of thermal mass in concrete framed buildings, combined with thermal improvements to the building envelopes (including walls and windows), results in energy savings up to 23% relative to the baseline steel framed EIFS buildings. This energy savings qualifies for up to four LEED-NC v2.2 points.

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