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EVALUATION OF ENERGY USE OF BUILDINGS WITH SINGLE WYTHE MASONRY WALLS CONSTRUCTED WITH LIGHTWEIGHT UNITS

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ABSTRACT

Both the demand and cost of energy is increasing as the population and economy of the United States continues to grow. This has prompted more energy efficient buildings to be designed and constructed. Although Energy Code provisions define alternative design methods that can be used to meet the energy efficiency requirements for a new building design, due to ease of use, most buildings are designed using the prescriptive approach.

Contrary to current prescriptive energy code provisions, modern exterior uninsulated mass masonry walls are expected to perform better with respect to energy use when the thermal mass effects and reduced thermal conductivities are accounted for. However, as most designers will use the prescriptive provisions of the IECC version adopted by the state where they are designing, they will be likely underestimating the impact that high thermal mass and lower conductivity walls will have on the performance of the buildings.

The following report describes an investigation designed to evaluate the impact light-weight low thermal bridging concrete masonry wall systems will have on the energy use of structures that are typically constructed with exterior mass masonry walls. Using three prototype commercial buildings based off the DOE building prototypes, a holistic energy study was conducted using a variety of exterior wall configurations to improve the energy performance of baseline models in order to evaluate their energy performance in the seven different Climate Zones in United States. The results of this study will be presented in the paper.

KEYWORDS: *energy analysis, uninsulated exterior light weight masonry walls*

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INTRODUCTION

The demand and cost of energy is increasing as the population and economy of the United States continues to grow. Exacerbating this increase in domestic energy demand is an even greater increase in the demand for energy by developing nations such as China and India. These significant increases, and thus costs, will negatively impact the US economy.

In recognition of the fact that a significant amount of energy in the US is used to heat, cool and light buildings, codes, standards and energy efficient guidelines for buildings have been developed by a number of organizations, including The International Code Committee (ICC) and ASHRAE. Furthermore, these documents are being continuously updated so that minimum levels of energy efficiency permitted by each has been steadily increasing.

The International Energy Conservation Code (IECC) [1] is referenced by the International Building Code (IBC) [2] an is the basis of energy related designs and also allows new designs to meet the provisions of ASHRAE 90.1 ANSI/ASHRAE/IESNA Standard 90.1, Energy Standard for Buildings Except Low-Rise Residential Buildings [3]. The IECC and ASHRAE 90.1 provisions both define two methods for meeting the energy efficiency goals with each new design. The first method is prescriptive in nature where minimum energy related characteristics of all significant elements within building are defined for different system types, space uses and climates. The second code design method requires a sophisticated whole building energy analysis to be conducted and compared to the same building designed using the prescriptive provisions; comparable economic energy performance is required. The IECC also provides for a system trade-off analysis (COMcheck) and complete building analysis options for energy code compliance. ASHRAE allows prescriptive and whole building analysis methods, as well as an envelope performance factor method. However, due to ease of use, most buildings are designed using the prescriptive approach.

In most climates in the US, the code mandated prescriptive envelope requirements would require that single wythe exterior masonry walls be continuously insulated with insulation R values varying from 1.004 m^2K/W to over 2.642 m^2K/W. As an alternative to the prescriptive insulation levels, thermal transmittance of the exterior envelope assemblies is prescriptively restricted to maximum values for different climates.

Furthermore, most of the design guides that have been developed for energy efficient design start with the assumption that increases in building envelope thermal resistance (R) are needed to improve building energy efficiency. Thus, most designers assume that a high R building envelope is needed for a building to be energy efficient. However, recent studies [4-7] have shown that increasing exterior wall R have only a minimal effect on the overall energy performance of the building, especially for exterior walls with a high thermal mass. Providing increases in the R of the building envelope will not necessarily result in a corresponding reduction in building energy use. It appears that after a certain point, more is not necessarily better with regards to envelope R. Similar behavior has also been found by researchers using climate conditions in some European cities [8]. This type of building energy performance is quite evident when more accurate energy analysis is conducted. However, most designers do not conduct these more time-consuming analyses. Designers generally use the prescriptive methods and thus are not achieving the most cost effective, nor most energy efficient building designs. Modern exterior uninsulated mass masonry walls are expected to perform better with respect to energy use when the thermal mass effects and reduced thermal conductivities are fully accounted for. The prescriptive code provisions will likely underestimating the impact that high thermal mass and lower conductivity walls will have on the performance of the buildings.

The two main advantage of building thermal mass in building energy consumption are shifting and reducing peak demands, since thermal mass absorbs heat when temperatures are high and gradually releases heat when temperatures are low. Shifting peak power consumption was stated as the most economically friendly approach on a short-term basis [9].

A number of studies have investigated the impact of thermal mass on building energy use. Zhou, Zhang et al. evaluated the indoor environmental impacts of six different external walls. They found that heavier walls had the lowest amplitude of indoor air temperature variation under the ventilation conditions investigated [10].They also found that when wall configurations were the same, locating insulation on external surface of the wall systems produced smaller fluctuations in indoor air temperatures [10]. In 2017, a study by Jevgeni Fadejev et al. showed that exterior walls with identical U-factors of 0.15 W/m^2K, but different thermal mass (the walls differed from wood to concrete) behaved differently. An initial reduction of 16% in cooling demand was found with a long term reduction about 5% with the higher thermal mass concrete wall system[11].

Others have evaluated methods to enhance the thermal mass effects. D. Olsthoorn et al. summarized four means of thermal mass activation: surface (night time ventilation of indoor spaces to reduce cooling demands), forced air (air ventilation through wall cavities), hydronic (fluid circulated through walls, roofs or floors), and direct electrical heating (electric coils in the walls and floors). These systems showed reductions in peak energy demand as high as 100% [9]. Those conclusions were confirmed by other researchers [12-15], as well.

However, increasing thermal mass does not always reduce building energy consumption. Suresh B. Sadineni et.al. investigated the impacts of a variety of energy saving strategies that emphasized the importance of improvement of building envelopes as passive energy saving strategies. They indicated that building thermal mass (including phase change material) is more effective in places where the outside ambient air temperature differences between the days and nights are high [16]. E. Rodrigues et al. indicated that the effect of thermal mass of buildings varied with climate conditions, methodologies, parametrization and settings [8]. This study showed that climate and thermal mass interacted, with high thermal mass walls producing better energy performance in some climates and not other [17]. It was generally concluded that increase of thermal mass increased the cooling energy demand and reduced the heating energy demand for warmer climates but may increase the heating energy demand for colder climates. However, higher thermal mass buildings on interior walls coupled with lower thermal mass on the exterior walls can improve energy behavior as well [8]. Thus, multiple factors can affect the impact of high mass walls on the energy use in buildings and further research is needed to investigate the energy saving potential of thermal mass of building envelopes.

Lightweight concrete walls often have less thermal mass than concrete made with conventional aggregates [18]. However, the previous studies indicate that there may an optimum thermal mass for a given climate. Thus, a research investigation was conducted on the energy performance of a variety of light weight masonry wall systems in a range of US climates. This research investigated the impact of thermal mass and a system of lightweight low thermal bridging concrete masonry wall systems have on the energy use of structures that are typically constructed with exterior mass masonry walls. The influence of thermal mass was analyzed through MATLAB and OpenStudio (Energy-Plus) holistic energy models [19] in 7 typical climate zones in U.S.

WALL THERMAL MODELLING USING MATLAB

A partial differential energy model [20] for an exterior wall was used to analyze the thermal flux through exterior walls, with a variety of materials with the same U-factor, but with different thermal mass. These models were used to investigate the impact of thermal mass on heat flux through walls over a 24-hour period. Each model simulated the wall behavior with an initial fixed interior temperature and a variable exterior temperature. The models were run for 48 hours in order to capture two 24-hour period diurnal cycles. The investigation focused on the wall responses of the second cycle to ensure the wall response was stable and minimize the impact of initial conditions. Four different exterior temperature regimes were used to simulate the hourly temperature variations for mild and extreme summer and winter temperature conditions. The indoor temperature setpoint was assumed to remain constant at 22°C. Expressions of temperature conditions are:

$$t = 31 + 8\sin\left(2\pi\left(x-10\right)/\left(24\right)\right) \quad (1)$$

$$t = 31 + 4\sin\left(2\pi\left(x-10\right)/\left(24\right)\right) \quad (2)$$

$$t = -4.75 + 8\sin\left(2\pi\left(x-10\right)/\left(24\right)\right) \quad (3)$$

$$t = -4.75 + 4\sin\left(2\pi\left(x-10\right)/\left(24\right)\right) \quad (4)$$

where x in hours, t in Celsius. These expressions were used to approximate design summer and winter weather conditions in U.S. Climate Zone 5, based on the historical temperatures record and then simplified to diurnal sine wave distribution for easier calculation.

Wall materials were assumed to be concrete and concrete masonry with the specific heats that varied from 560 to 960 to 1360 J/kgK (low, middle or high thermal mass, “L”, “D”, “H”), and with

U-factors of 2.244 W/m^2K (insulated, "I") or 0.290 W/m^2K (non-insulated, "NI"). The results of this analysis is discussed later in paper.

HOLISTIC ENERGY BUILDING ENERGY MODELLING

In general, when different wall configurations are used in a building, both the U-factor and thermal mass of the wall system will vary. For example, concrete or concrete masonry walls with a larger thermal mass often has a larger U-factor. It is generally believed that larger thermal mass contributes to energy saving, but larger U-factors allow greater thermal losses and gains. This makes the analysis of thermal mass complicated. In an effort to assess the realistic impacts of thermal mass, changes in wall U-factors corresponding to typical changes in thermal mass must also be considered. To assess these impacts, a holistic building energy analyses of three different prototype buildings were conducted. These analyses compared the yearly energy performance of the prototype buildings with code prescriptive insulation configurations (baseline configurations) and three exterior mass wall configurations with varying thermal masses and U-factors. Each of the three prototype buildings were analyzed using hourly weather data from the seven cities shown in Table 1. These seven cities are representative of the seven Climate Zones in the U.S [1].

Table 1: Representative Cities of ASHREA Climate Zones

City	State	Zone
Miami	FL	1A
Houston	TX	2A
Las Vegas	Nevada	3B
Seattle	Washington	4C
Chicago	Illinois	5A
Minneapolis	Minnesota	6A
Duluth	Minnesota	7

Three building prototypes were selected. These prototypes were selected to be representative of buildings commonly constructed with exterior concrete masonry (or concrete) walls. The first prototype was a secondary school, the second was a supermarket. And the third prototype evaluated in this study was based on the supermarket model but modified to remove the bakery, deli, produce section and the cooler equipment (designated Supermarket (Modified)). A previous study by the authors showed that this building configuration was consistent with a number of typical "box retail" facilities [7]. The secondary school and supermarket prototype building models (in the baseline configuration) were among the sixteen prototypes developed by the U.S. Department of Energy (DOE) [19] to be representative of these building types. OpenStudio (EnergyPlus) analysis were conducted on each. These energy analyses were conducted using hourly weather data from the seven cities shown in Table 1.

The three additional exterior wall configurations were selected to be representative of commonly used exterior wall systems as an alternative to the baseline, grouted insulated exterior masonry wall systems. The baseline configuration of the exterior walls included interior insulation and furring strips with interior gypsum wall board set to code prescriptive levels for each climate zone. The U factors used for the energy modelling of the baseline configurations for the seven Climate Zones are listed in Table 2. The first alternative exterior wall assembly configuration used a single wythe 300 mm (12 in.), heavy weight CMU (2162 kg/m^3 - 135 pcf) with reinforced cores at 1220 mm (48 in.) OC. The remainder of the cores were filled with aminoplast foam insulation. The U-factor for this wall was 1.100 m^2K/W (0.194 Btu/hft^2F). Prototype models with this wall configuration were identified as "Wall-01". The second alternative wall assembly used lightweight CMU units (1682 kg/m^3, 105 pcf) reinforced at 1220 mm (48 in) OC with foamed insulation in ungrouted cells. This wall configuration also included 50 mm (2 in) rigid insulation inserts in the grouted cells (U=0.591 m^2K/W, 0.104 Btu/hft^2F). Prototype models with this wall configuration were identified as "Wall-02". The third alternative wall assembly used 2-web lightweight CMU unit (1490 kg/m^3, 93 pcf), reinforced at 1220 mm (48 in) OC with foam insulation in ungrouted cells. This configuration also included 50 mm (2 in) rigid insulation inserts in the grouted cells (U=0.386 m^2K/W, 0.068 Btu/hft^2F). Prototype models with this wall configuration were identified as "Wall-03". Each of the wall types have different thermal masses, as well as different U factors.

Table 2: Prescriptive (Baseline) Envelope U-Factors for Seven Climate Zones. Units: W/m^2K or (Btu/hft^2F)

Climate Zone	City	Roof	Floor	Wall
1A	Miami	0.273 (0.048)	1.828 (0.322)	0.863 (0.152)
2A	Houston	0.221 (0.039)	0.608 (0.107)	0.863 (0.152)
3B	Las Vegas	0.221 (0.039)	0.432 (0.076)	0.698 (0.123)
4C	Seattle	0.182 (0.032)	0.432 (0.076)	0.591 (0.104)
5A	Chicago	0.182 (0.032)	0.42 (0.074)	0.511 (0.090)
6A	Minneapolis	0.182 (0.032)	0.363 (0.064)	0.454 (0.080)
7	Duluth	0.159 (0.028)	0.312 (0.055)	0.403 (0.071)

RESULTS AND DISCUSSION: MODEL ANALYSIS

It is clear from the previous discussion that thermal mass can reduce the rate of heat transferred to the indoor environment from ambient. Figure 1 shows a typical temperature response of surfaces of wall assembly in a mild summer weather with different specific heats based on partial differential thermal flux analysis. Higher thermal wall mass contributes to larger peak shifting (T_{LAG}), as well as lower interior surface temperature amplitude (T_{AMPL}). The delay in peak temperature supports off-peak consumption. A smaller T_{AMPL} value means the temperature of interior wall surface would vary less and reduce the amount of energy needed to maintain interior air temperatures a given time. The temperature difference between the mean interior surface of wall and the indoor air, $T_{d,\,m}$, can be used as an indicator of total interior energy demand.

Figure 2 shows the peak temperature lag for the various wall configurations. It can be seen that it increases in thermal mass delay of peak temperature increases in a roughly linear manner for the range of wall densities investigated. It can also be seen that the lag times are almost identical in winter and summer with the same wall configurations. The trendlines indicate that, as the thermal mass increases, the impact on T_{LAG} is smaller and tapers off at an upper limit. This result suggests that, with a proper thermal mass design, the time to peak temperature of the interior envelope surface can be shifted several hours later than the hottest time in summer. This tailored exterior wall mass can be used to reduce peak energy consumption for heating and cooling.

It must be pointed out that the simulations show no significant variation in $T_{d,m}$ (less than 0.3%) with thermal mass in the winter or summer. Thermal mass hardly impacts the total energy required for heating or cooling if the indoor temperature was maintained at a set value (and not to vary). Figure 3 shows the variation of T_{AMPL} with exterior wall specific heat in different weather conditions.

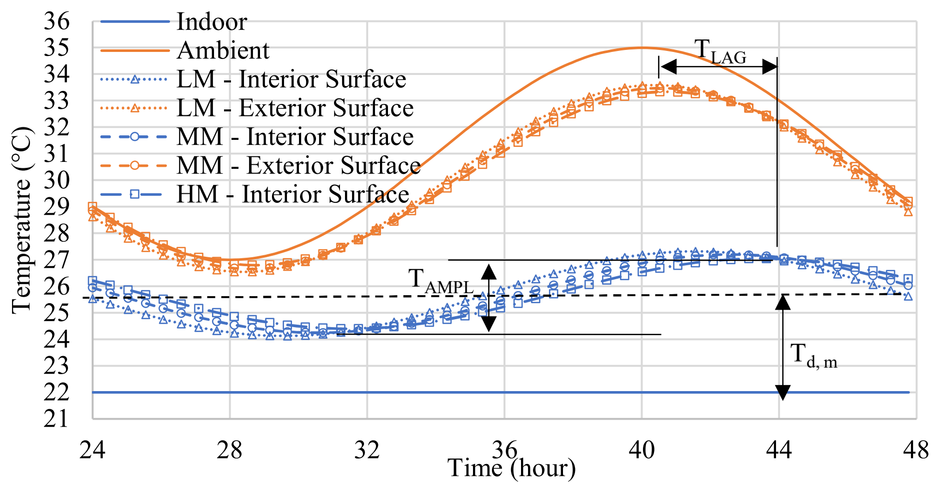


Figure 1: Temperature Response of Wall Surfaces in a Mild Summer Weather with Different Exterior Wall Specific Heats

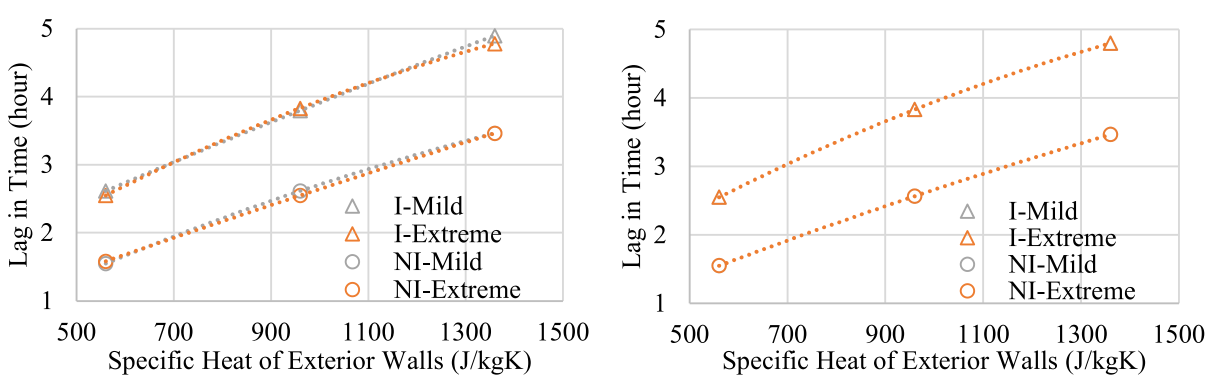
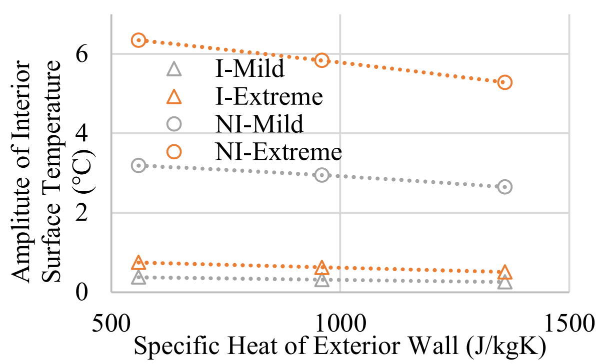


Figure 2: T_{LAG} of Wall with Different Exterior Wall Specific Heat in Summer (Left) and Winter (Right)

Figure 3 shows that increases in exterior wall thermal mass produce smaller changes in interior surface temperature. This lower surface temperature variation means higher thermal mass reduced the changes in surface temperature. In poorly insulated wall configurations, this effect is more significant, which suggests that the impact of thermal mass is more significant when the exterior wall's U-factor is high.

Examining both Figure 1 and 3 also suggests that changes in thermal mass do not impact $T_{d,\ m}$, significantly and total energy demand may not be greatly impacted by the mass. However, as T_{AMPL} decreases, the maximum cooling demand will decrease. Furthermore, in this analysis, the indoor temperature was set to a fixed value. In actual building operation, the HVAC system control will operate over a range of temperatures (the dead-band). Thus, the interior temperature will not be constant. Furthermore, when interior temperatures are within the dead-band range there will be no heating or cooling energy demand. Thus, the variation in the exterior wall interior surface temperature may not directly correlate to energy demand if interior temperatures are allowed to rise and fall. Therefore, to assess actual energy consumption, analyses must account for thermal mass, interior set points and dead-bands in order to get an accurate estimate of energy consumption. Holistic modeling is this needed to fully define these quantities.



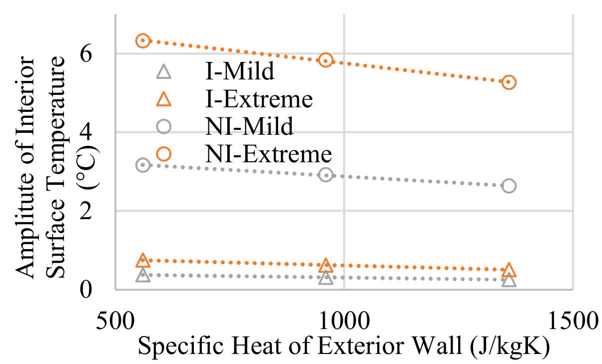


Figure 3: T_{AMPL} of Walls with Different Specific Heats in Summer (Left) and Winter (Right)

RESULTS AND DISCUSSION: HOLISTIC ANALYSIS

Figure 4 shows the typical energy use of a secondary school building in Climate Zone 5 by end use. Heating and cooling of the prototype building accounts for roughly 1/3 of the total yearly energy consumption. As discussed previously, this portion of the building energy use will be impacted by heat flux through the building envelope, including the exterior masonry walls.

The U-factors of the four wall configurations studies in this investigation notably varies, the U-factor of Wall-03 was only a third of Wall-01. Therefore, energy consumption with the four wall configurations would be expected to vary greatly by most designers. Figures 5 to 7 showed the total yearly energy consumption of the three prototypes studied with different wall configurations. In warm climate zones like 1A, 2A and 3B, energy consumption of buildings with the four different wall configurations does not change much, especially in 1A, the annual energy consumption difference is within 0.1%. Even when the prototype building was evaluated under Climate Zone

4C, 5A, 6A, and 7 weather, energy consumption varied only from about from 2% to 8% over large changes in exterior wall configurations. In supermarket prototype building simulations, the variation in energy used was only about 5%, slightly less than in other two type of buildings. This was most likely because that refrigeration accounts for a huge part of the total energy consumption.

It can be concluded that U-factor and thermal mass of exterior mass walls can significantly impact energy consumption of buildings in Climate Zones 4 to 7, where heating demands are high.

The U-factor of two of the alternative exterior masonry wall configurations without external insulation, configuration Wall-02 and Wall-03, have smaller U-factor values than the limits in the prescriptive code requirements in some Climate Zones, and are thus code compliant. The lower U-factor values of these walls compared to the code U-factor limits will the reduce heat flux through envelopes and thus reduce the HVAC energy consumption of the buildings. For most of the three protypes, Figures 5 to7 show that alternative exterior wall configuration, Wall 03, showed lower energy consumption than the baseline values (code compliant) in all climates but one (Climate Zone 7). Alternative exterior wall configuration, Wall 2, showed lower energy consumption than the baseline values (code compliant) up to Climate Zone 3B. In addition, for the three building prototypes studied, the building energy consumption for configuration having exterior walls configured as Wall-02 in Climate Zone 4C and Wall-03 in Climate Zone 7 were slightly greater than baselines prototype. This result would suggest that the energy budget method code compliance would not allow the wall configurations in these two cases, yet the prescriptive method using the U-factor of the wall assembly would. The result also suggests that in (very cold) Climate Zone 7, the energy saving potential of thermal mass may be more significant, especially after a minimum U-factor value is met. In cases where exterior walls are configured as Wall-02 in in Climate Zone 4C or code compliant, the difference in total energy consumption was less than 0.15%, so it is not considered significant.

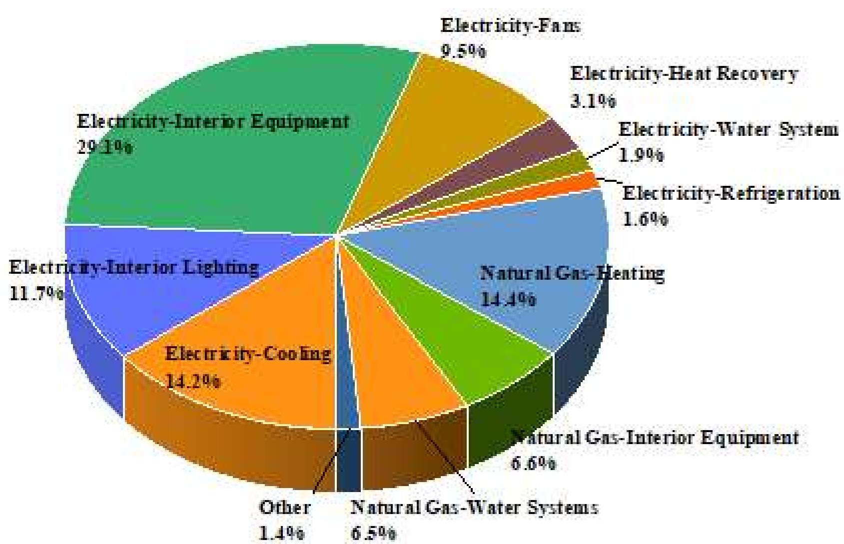
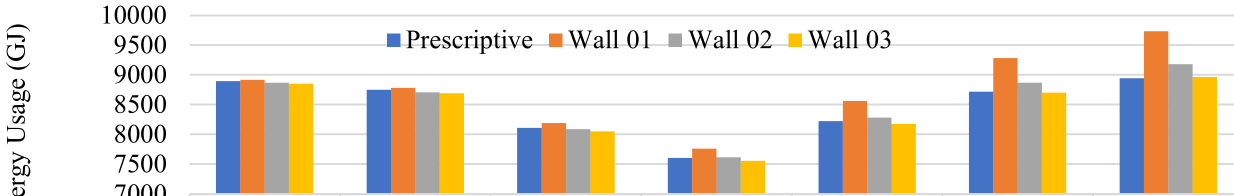
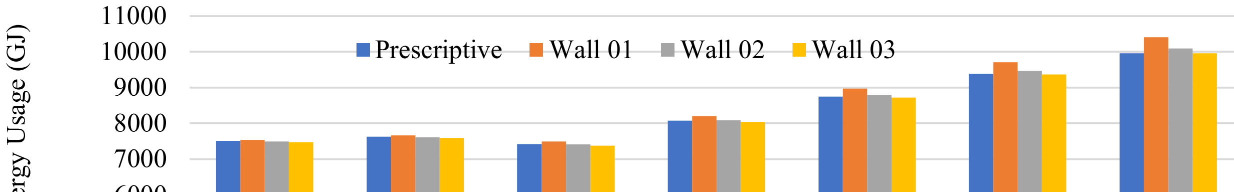


Figure 4: Energy Usage of Prescriptive Supermarket Prototype in Climate Zone 5



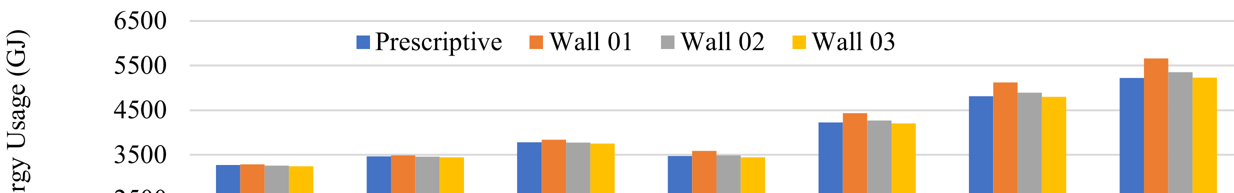
	Miami 1A	Houston 2A	Las Vegas 3B	Seattle 4C	Chicago 5A	Minneapolis 6A	Duluth 7
Prescriptive	8892.42	8750.73	8110.82	7605.07	8219.25	8718.53	8943.97
Wall 01	8914.95	8778.81	8191.91	7759.79	8559.5	9278.6	9733.48
Wall 02	8869	8704.64	8085.25	7614.86	8280.2	8864.32	9176.03
Wall 03	8850.94	8691.53	8048.42	7555.75	8173.67	8702.03	8965.27

Figure 5: Total Yearly Energy Use of Secondary School Prototype



	Miami 1A	Houston 2A	Las Vegas 3B	Seattle 4C	Chicago 5A	Minneapolis 6A	Duluth 7
Prescriptive	7509.95	7625.58	7417	8075.42	8747.42	9383.1	9951.72
Wall 01	7533.4	7657.39	7490.24	8195.96	8965.17	9700.74	10403.29
Wall 02	7492.3	7608.71	7409.01	8081.52	8788.11	9461.41	10084.85
Wall 03	7473.72	7589.79	7376.3	8034.83	8715.82	9364.27	9955.46

Figure 6: Total Yearly Energy Use of Supermarket Prototype



	Miami 1A	Houston 2A	Las Vegas 3B	Seattle 4C	Chicago 5A	Minneapolis 6A	Duluth 7
Prescriptive	3269.72	3463.26	3777.75	3474.98	4224.81	4812.38	5222.13
Wall 01	3285.92	3488.52	3837.37	3583.47	4428.61	5118.27	5657.18
Wall 02	3253.52	3456.4	3772.81	3482.9	4265.13	4889.25	5351.33
Wall 03	3243.69	3443.54	3748.87	3444.18	4201.53	4797.57	5228.81

Figure 7: Total Yearly Energy Use of Supermarket (Modified) Prototype

CONCLUSIONS

The results of the analysis presented suggest that thermal mass of the exterior walls, combined with U-factor impacts the energy flux through exterior walls.

For the three prototype buildings investigated, buildings with exterior wall assemblies of lightweight CMU units reinforced at 48" OC, with foam insulation in empty cells and with a 2" rigid insulation insert in the grouted cells (U=0.591 m^2K/W, 0.104 Btu/hft^2F were generally code compliant in Climate Zones 1A, 2A and 3B. In Climate Zone 4C, the buildings were either showed code compliance (less yearly energy usage) or have similar yearly energy use, generally within 0.4% of the baseline and well within the accepted accuracy of the energy simulation software. These results are also consistent with that predicted by the prescriptive U-factor compliance method.

For all three prototype buildings, building configurations which used exterior wall assemblies of 2-web lightweight CMU units reinforced at 400 mm (48 in) OC with foamed insulation in the ungrouted cells and 50 mm (2 in) and rigid insulation inserts in the grouted cells (U=0.386 m^2K/W, 0.068 Btu/hft^2F). labeled 12" SW 2 Web were shown to be code compliant in all but Climate Zone 7. Furthermore, it could be argued that these configurations are also code compliant in Climate Zone 7, as the yearly energy use is close to baseline values and within the accepted accuracy of the energy simulation software. In addition, these wall systems would meet the code prescriptive limits on wall assembly U factors and thus show code compliance through this route.

In general, for all the evaluated building configurations and climates, a 200 to 300 % change in wall thermal resistance resulted in less than an 8% change in yearly energy use.

REFERENCES

[1] (2014) International Energy Conservation Code 2015, International Code Council.
[2] (2014) International Building Code 2015, International Code Council.
[3] ASHRAE. (2013) ASHRAE 90.1-2013 Energy Standard for Buildings Except Low-Rise Residential Buildings.
[4] McGinley, M. W. (2011) Cost Effective Energy Efficient School Design-Applied Research, In Energy and Buildings, Department of Civil and Environmental Engineering, University of Louisville.
[5] Kiesel, J. D., and McGinley, W. M. (2015) Development of Concrete Incorporating Phase Change Materials, In 12th North American Masonry Conference, Denver, CO.
[6] McGinley, W. M., and Beraun, D. (2015) An investigation of Alternative Energy Efficient Medium Sized Single Wythe Masonry Warehouse Buildings In 12th North American Masonry Conference, Denver, CO.
[7] McGinley, W. M., and Beraun, D. (2015) An investigation of Alternative Energy Efficient Medium Sized Single Wythe Masonry Supermarket and Box Retail Buildings, In 12th North American Masonry Conference, Denver, CO.

[8] Rodrigues, E., Fernandes, M. S., Gaspar, A. R., Gomes, Á., and Costa, J. J. (2019) Thermal transmittance effect on energy consumption of Mediterranean buildings with different thermal mass, Applied Energy 252.
[9] Olsthoorn, D., Haghighat, F., Moreau, A., and Lacroix, G. (2017) Abilities and limitations of thermal mass activation for thermal comfort, peak shifting and shaving: A review, Building and Environment 118, 113-127.
[10] Zhou, J., Zhang, G., Lin, Y., and Li, Y. (2008) Coupling of thermal mass and natural ventilation in buildings, Energy and Buildings 40, 979-986.
[11] Fadejev, J., Simson, R., Kurnitski, J., and Bomberg, M. (2017) Thermal mass and energy recovery utilization for peak load reduction, Energy Procedia.
[12] Kuczyński, T., and Staszczuk, A. (2020) Experimental study of the influence of thermal mass on thermal comfort and cooling energy demand in residential buildings, Energy 195.
[13] Hu, M., Xiao, F., Jørgensen, J. B., and Li, R. (2019) Price-responsive model predictive control of floor heating systems for demand response using building thermal mass, Applied Thermal Engineering 153, 316-329.
[14] Jimenez-Bescos, C. (2017) An Evaluation on the Effect of Night Ventilation on Thermal Mass to Reduce Overheating in Future Climate Scenarios, In CISBAT 2017 International Conference - Future Buildings & Districts - Energy Efficiency from Nano to Urban Scale, Elsevier Ltd., Lausanne, Switzerland.
[15] Alonso, M. J., and Mathisen, H. M. (2017) Analysis of Reduction of Energy Demands for Zero Emission Renovated Office Building by Using Thermal Mass and Ventilative Cooling, In 11th Nordic Symposium on Building Physics, Elsevier Ltd., Trondheim, Norway.
[16] Sadineni, S. B., Madala, S., and Boehm, R. F. (2011) Passive building energy savings: A review of building envelope components, Renewable and Sustainable Energy Reviews 15, 3617-3631.
[17] Idris, I. H. M., and Yusof, N. Z. (2018) Development of low thermal mass cement-sand block utilizing peat soil and effective microorganism, Case Studies in Construction Materials 8, 8-15.
[18] Cavalline, T. L., Castrodale, R. W., Freeman, C., and Wall, J. (2017) Impact of Lightweight Aggregate on Concrete Thermal Properties, ACI Materials Journal 114.
[19] Deru, M., Field, K., Studer, D., Benne, K., Griffith, B., Torcellini, P., Liu, B., Halverson, M., Winiarski, D., Rosenberg, M., Yazdanian, M., Huang, J., and Crawley, D. (2011) U.S. Department of Energy Commercial Reference Building Models of the National Building Stock, pp 1-118, National Renewable Energy Laboratory.
[20] (2020) Partial Differential Equation Toolbox™ User's Guide, The MathWorks, Inc.