MODELING THE THERMAL CHARACTERISTICS OF MASONRY MORTAR CONTAINING RECYCLED MATERIALS

by

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ABSTRACT

MORGAN GRETCHEN LANEY. Modeling the thermal characteristics of masonry mortar containing recycled materials. (Under the direction of DR. THOMAS NICHOLAS II)

As the building industry in the United States rapidly expands, the reuse of recycled demolition waste aggregates is becoming increasingly more important. Currently, the building industry is the largest consumer of natural resources. The constant use of raw virgin aggregate is resulting in depleting resources, lack of space for landfills, increasing costs, and heightened levels of pollution. The use of these recycled aggregates in building envelopes and the study of thermal properties are becoming a popular area of research in order to improve building energy usage. The construction of Zero Energy Buildings (ZEB) is encouraged by the United States government as a result of the unresolved finite resources and environmental pollution. The focus of this research is on the impact of using recycled demolition waste aggregates on thermal properties, including specific heat capacity and thermal conductivity, in masonry mortar applications. The new forms of aggregate were analyzed for efficiency and practical utilization in construction in seven locations across the United States by embedding the new material into the building envelope of a strip mall mercantile build model from the National Renewable Energy Laboratory (NREL) in the EnergyPlus Building Energy Simulation Program (BESP). It was determined that the recycled aggregate mortar mixtures performed as well as or better than the traditional mortar mix. Opportunities for future research in recycled aggregate mortar mixtures exist in a regional analysis, a regional recycled aggregate cost analysis, and a life cycled cost analysis (LCCA).

ACKNOWLEDGMENTS

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ASHRAE	American Society of Heating, Refrigerating, & Air-Conditioning Engineers
BESP	Building energy simulation program
BTU	British thermal unit
DOE	Department of Energy
DSC	Differential scanning calorimetry
EEFG	EnergyPlus™ Example File Generator
EERE	Energy Efficiency and Renewable Energy
EMPD	Effective Moisture Penetration Depths
GJ	Gigajoule
GUI	Graphical user interface
HVAC	Heating, ventilation, and air conditioning
IECC	International Energy Conservation Code
IRS	Internal Revenue Service
LCCA	Life cycle cost analysis
LEED	Leadership in Energy & Environmental Design
LW	Lightweight
NREL	National Renewable Energy Laboratory
NW	Normal weight
PCA	Portland Cement Association
RBMA	Recycled brick masonry aggregate
RCA	Recycled concrete aggregate

USGBC	United States Green Building Council
ZEB	Zero Energy Buildings

CHAPTER 1: INTRODUCTION

1.1 Problem Statement

The United States Department of Energy (DOE) reported in 2012 that the building industry is the largest consumer of natural resources with total energy use at 41% of the industry (U.S. Department of Energy, 2012). The building industry is not only the largest consumer of energy but buildings alone consume 73% of the electricity in the United States. It is estimated that by 2035 buildings will consume a total of 77.2% of the nation's electricity with commercial buildings consuming 38.4% of the reported total. Less than 1% of the energy produced is renewable; the remaining relies on natural gas, petroleum, and coal. The dependence on natural resources results in a total of 38% of all of CO_2 emissions coming from the building industry (U.S. Green Building Council, 2011).

The focus of this research is on the impact of using demolition waste aggregates on the thermal properties, including specific heat capacity and thermal conductivity, in masonry mortar and grout applications. As the demand for aggregate increases with the demand for new construction, aggregate will become sparse and increase in cost. By using building energy simulation programs (BESP), the new forms of aggregate can be analyzed for energy efficiency and practical utilization in construction.

Figure 1 shows the predicted primary energy use by sector from 2011 to 2040 in quadrillion BTUs. Currently, the commercial sector accounts for a predicted 3.1 quadrillion BTU increase from 2011 to 2040 coming in second to industrial. Despite the increased use of recycled building materials and airtight building envelopes, the commercial sector energy use is increasing substantially more than others at an annual increase of 0.5 percent. This is due to an average annual 1.6% increase in constructed commercial floor space (U.S. Energy Information Administration 2013). The Department of Energy (DOE) reported in 2005 that offices comprise 18% of the total floor place and 22% of the primary energy consumption. Offices, mercantile, and educational facilities combined consume nearly half the commercial sector energy use (Waide et al. 2007).

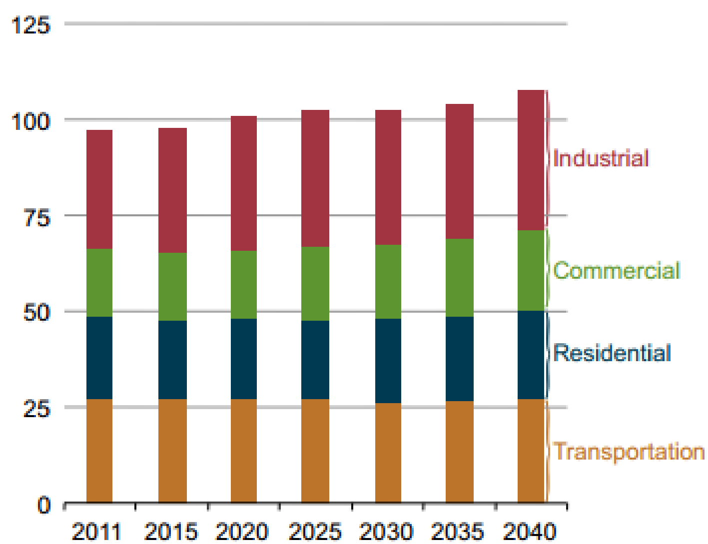

Figure 1: Prediction of primary energy use by sector through 2040
(quadrillion BTU vs. year) (U.S. Energy Information Administration, 2013)

If 20% of the energy use in buildings is cut, about $80 billion could be saved annually on energy bills (Crawley 2010). In response to the increasing energy demands for commercial buildings, the DOE created the Energy Efficiency and Renewable Energy (EERE) program. EERE in 2005 set a goal of a 20% reduction in energy use by 2020 (U.S. Department of Energy, 2013) and a 17% reduction in greenhouse gas emissions by

2020 (Crawley, 2010). This is an attempt to create Zero Energy Commercial Buildings by 2025. Zero Energy Buildings (ZEB) create enough on-site renewable energy to offset the drawl from the electricity grid therefore reducing the amount of natural resources consumed.

Due to the increased popularity of commercial ZEBs, the improvement of thermal properties of building envelopes has become a popular research area. ZEBs can be achieved through a performance based design/build process. The design/build process heavily involves the selection and use of energy efficient materials in the building. To date, very little research has been performed on the thermal properties of recycled demolition waste aggregates in masonry mortar.

On average, annually every American consumes about 10 tons of aggregate (U.S. Army Corps of Engineers, 2004). Figure 2 displays the percentage increase of aggregate demand for the overall raw material consumption in the United States from 1900-1998 (Goonan, 2000). From 1900-1958, the demand increased by a factor of 1.15 percent annually and has maintained an average of about 70 percent of the total raw material demand since 1958 (Goonan, 2000). As the United States infrastructure ages, it is replaced, annually creating nearly 200 million metric tons of recycled aggregate that either is reused or placed into a landfill (Goonan, 2000). As landfill space becomes scarce it is even more important to reuse the recyclable materials in new construction and retrofits. In 2004, the U.S. Army Corps of Engineers recorded that 8,000 buildings, equaling about 50 million square feet, once used for military installation were to be demolished (U.S. Army Corps of Engineers, 2004). Instead of demolishing these facilities and dumping the materials into landfills, it was proposed that the materials be recycled. The recycled material is used in many applications including concrete mixes, asphalt mixes, riprap, road beds, general fillers, and other applications (Goonan, 2000).

Reducing the impact of the construction industry on the environment is becoming an increasing concern for environmental and economic purposes. Due to limitations and restrictions, new quarrying sites are becoming less common and processing costs are skyrocketing (ECCO, 1999). The increasing cost of facilities operating, transporting, and processing for the quarrying of common virgin raw natural aggregate raises the cost of construction significantly (Gilpin et al., 2004). Common demolition and construction rubble consists of crushed block, brick, and concrete that can be reused in many applications. Additionally, the availability of suitable landfill sites for demolition rubble and municipal solid waste are becoming less abundant making it a more economical option to reuse post-industrial waste (Gilpin et al., 2004). Organizations, such as Leadership in Energy & Environmental Design (LEED), offer incentives for sustainable construction and reuse of materials.

Due to the growing energy consumption of commercial buildings and the demand for aggregate in construction, it is increasingly more important to find methods to recycle demolition rubble and municipal solid waste in new construction and retrofits. By developing a model using BESP for a concrete masonry structure using increasing levels of recycled concrete aggregates (RCA) used in mortar applications, a comparative analysis can be performed on the specific heat capacity and thermal conductivity of standard masonry and RCA variations. These new forms of aggregate will be analyzed for energy efficiency and practical utilization in construction.

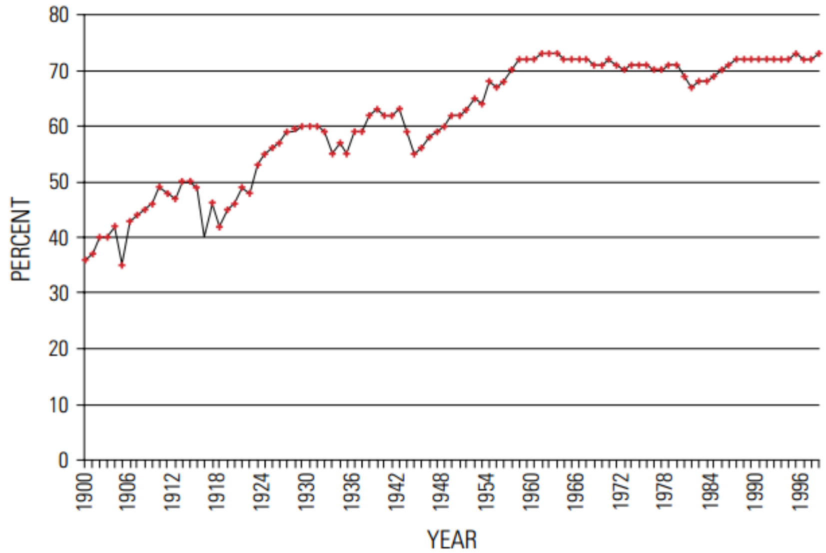

Figure 2: U.S. construction aggregate virgin raw material consumption, 1900-1998 (U.S. Army Corps of Engineers, 2004)

1.2 Objectives and Scope of Study

The specific objectives of the study are to:

- Develop models using building energy simulation programs (BESP) for a concrete masonry structure using conventional aggregates and recycled aggregates,
- Perform simulations of multiple BESP models that utilize increasing levels of recycled concrete aggregate (RCA),
- Perform a comparative analysis between standard masonry and RCA variations.

1.3 Organization of Thesis

This thesis consists of five chapters and is organized in the following way; the first chapter is the introduction and presents the problem statement and thesis scope. Chapter two is a literature review that discusses research that coincides with the thesis topic and shows a need for current research. Chapter three discusses the research methodology involved in BESP modeling. The fourth chapter includes results and discussion from BESP outputs. Lastly, chapter five covers future work and how to move forward.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

With the increasing concern of the impact of the construction industry on the environment, incorporating recycled aggregates into new construction is becoming more popular. Research is being performed in many areas in order to build facilities that impact the environment minimally from the construction and materials phase to the lifelong energy consumption. As the industry focuses on building energy efficiency and Zero Energy Buildings, a new generation of energy conservation codes and building energy simulation programs (BESP) have been developed. Concrete masonry construction can provide significant benefits to owners due to the fact that it is energy efficient, can be locally produced, a natural material with a long life expectancy, and can incorporate recycled materials (Graber et al., 2012).

A number of studies have been conducted internationally on the use of municipal solid waste and construction and demolition waste as aggregates in various applications but very little research has been performed on this topic in the United States. Overall, the majority of the research performed on these alternative forms of aggregates has been in roadbeds and concrete applications (Exteberria et al., 2006). Very little research was found in the area of mortar and grout applications.

Substituting recycled aggregates in place of raw virgin aggregates in mortar applications allows buildings constructed with concrete block to be a more sustainable option. Determining the thermal characteristics of masonry mortar and grout produced using recycled and waste materials to replace conventional aggregates will allow for an extensive thermal analysis of buildings with masonry walls through BESP.

2.2 Reuse of Construction Waste in Cementitious Applications

Since continuous development is occurring country wide and roads and facilities are being demolished, knowing how to counteract waste produced is of high importance. Unfortunately, recycling construction materials is not a widely accepted practice due to a poor image and a lack of certainty in the quality of the finished product. Factors such as low dumping costs for landfills also have a direct effect on how the construction industry and municipalities choose to dispose of waste (Jha et al., 2007). The low dumping costs have become competitive with recycled aggregate reuse costs.

Even though there are challenges associated with the use of recycled material in the construction industry, the benefits far outweigh the disadvantages. Construction and demolition waste have been successfully used in various construction applications. An example of recycling construction materials is in the use of building rubble and brick in structural applications (Exteberria et al.,2006). There are many more advantages to recycling construction and demolition waste that are discussed in the following sections.

2.2.1 Construction and Demolition Waste

Construction and demolition waste is defined by the Environmental Protection Agency (EPA) as “the waste material produced in the process of construction, renovation, or demolition of structures,” (2012). According to Gilpin et al. (2004) an estimated amount of 2.7 billion metric tons of aggregates is used in the United States. Out of the 2.7 billion metric tons of aggregate, pavement accounts for 10-15%, general road construction and maintenance accounts for 20-30%, and the remaining 60-70% is used in structural concrete. Construction and demolition waste can consist of crushed concrete, bricks, and pavement (Jha et al., 2007). Recycled aggregates can come from a number of sources including raw virgin aggregates producers, contractors, and debris recycling centers (Gilpin et al., 2004). Even if a small percentage of these aggregates were recycled, the environmental impact of the construction industry would be significantly reduced.

Exteberria et al. (2006), investigated recycled concrete aggregates in a structural application. It was determined that up to 25% of aggregates in traditional concrete beams could be replaced without compromising the structural integrity. Another type of construction and demolition waste was tested by Cavalline and Weggel (2013). Recycled brick masonry aggregate (RBMA) was substituted as the aggregate in concrete and tested in roadbed applications. It was determined that RBMA was indeed a suitable substitute for raw virgin aggregate but further investigation is required due to the lack of prior research.

Currently, research has been performed in many countries on the use of recycled aggregates in concrete and road construction applications. Unfortunately, recycling aggregates is still an unfamiliar materials method in the United States. The first instance in which recycled aggregates were used in concrete was after World War II (Khalaf and DeVenny, 2004). Since then, several countries have performed research on the uses of recycled aggregates and the results appear promising (Jha et al., 2007).

2.2.2 Advantages of Recycled Aggregates

The use of recycled aggregates in the application of mortar in concrete block construction provides many advantages to the industry. According to Tam et al. (2006), recycling waste is becoming a more attractive option due to decreasing availability of raw virgin aggregates, increasing landfill fees, and dwindling landfill space. Unfortunately, the majority of construction and demolition waste goes to landfills therefore directly contributing to these issues. The increased cost can make the use of recycled aggregates a more attractive option.

Before lightweight construction options were available, concrete masonry was the primary material used in building construction. The thickness and density of concrete masonry construction material allows for prime thermal mass characteristics. According to Graber et al. (2010), “thermal mass describes the ability of materials to store heat.” Concrete masonry provides effective thermal storage due to its high density and specific heat properties. The material ultimately allows buildings to have reduced heat and cooling loads, decreases indoor temperature swings, and can shift loads to off-peak hours (Graber et al., 2010). By replacing the conventional aggregates used in mortar and grout applications, concrete masonry can be an effective option in sustainable building construction.

Due to the large effect block, brick, and concrete have on the environment, reuse incentives are an attractive option for the construction industry. Organizations such as Leadership in Energy & Environmental Design (LEED) under the U.S. Green Building Council (USGBC) offer incentives for materials reuse and recycled content as well as guidance for quality control and assurance. This reduces the impact of extraction and processing of virgin raw materials. One point is acquired for 10 percent recycled materials and two points for 20 percent recycled materials (Leadership in Energy and Environmental Design). Additional points are awarded for use of regional materials.

2.3 Use of Recycled Materials in Concrete Masonry Mortar

Many types of recycled materials have been studied for use in concrete and concrete masonry applications but very few have been studied for reuse in concrete masonry mortar. Those that have been studied often have sufficient structural strength and are sustainable substitutes for natural sand mortars.

Ledesma et al. (2014) researched the use of fine recycled aggregate from concrete masonry waste. The recycled concrete masonry aggregate was obtained from a recycling plant that crushed, sieved, and removed reinforcing steel from the aggregates before distribution. It was found that up to 40% of the natural sand could be replaced with the fine recycled aggregate; however there were some negative effects. The fine recycled aggregate mortars stayed wet for a longer period of time. This was due to the inability of water to evaporate from the mortar. The final results showed that there was no difference in structural strength between the natural sand mortar and the fine recycled aggregate.

Another study performed in Cuba analyzed 100% replacement of the natural sand in the mortar mix with demolished houses (Martínez et al., 2013). The demolition waste aggregate obtained from the houses consisted of ceramic, mortar, and concrete masonry. It was proven through testing that the recycled mortar variations performed as well as the natural sand mortars and often improved the mortar properties. Martínez et al. (2013) states that “this improvement was due to both the adequate size grading distribution of the recycled aggregates and the low quality of natural aggregates located in Havana, Cuba.” Despite the low quality of the natural aggregates, a more environmentally conscious substitute was found.

2.4 BESP and EnergyPlus™ Background

EnergyPlus is the U.S. DOE's robust building energy simulation program (BESP). EnergyPlus was selected for a BESP investigation due to its ability to comprehensively provide an energy analysis and thermal load simulation (U.S. Department of Energy, 2013). This program fully integrates buildings, envelopes, HVAC, water, and renewables simulations. Being one of the world's most robust energy simulation programs, EnergyPlus integrates energy performance analysis of low-energy technologies in commercial and residential buildings including on-site generation and renewable energy sources. It is designed for weather data analysis for more than 2,100 locations worldwide, flexibility and expansion of building energy options, new low-energy technologies, sub-hourly calculations, outputs in the form of energy, water, and emissions, and 3,800 pages of documentation and validation reports (Crawley, 2010). EnergyPlus allows engineers, architects, and researchers to model energy and water use in buildings therefore allowing designers to optimize building processes (U.S. Department of Energy, 2013).

There are several famous commercial buildings that used EnergyPlus in the design process that have specific energy demands and environmental goals including a full building energy simulation, code compliance, energy use impacts, thermal simulations, climate analysis, and natural ventilation displacement. These buildings include the Freedom Tower, New York Times building, San Francisco Federal building, and the San Diego Supercomputer Center (Crawley, 2010).

Based on a building's physical characteristics, EnergyPlus will calculate heating and cooling loads necessary to maintain ideal thermal control points, conditions through a secondary HVAC system and coil loads, and the energy demands of primary equipment. EnergyPlus models heating, cooling, lighting, ventilation, miscellaneous energy flows, and water use (U.S. Department of Energy, 2013). Therefore allowing design teams and owners to focus on reducing energy-use and where these efforts would be most effective. EnergyPlus also allows for informed energy decisions from earliest phases of design through construction and operation, helps the design team and owner focus energy-use reduction efforts where most effective, permits assessment of predicted performance with established benchmarks, sizes renewable energy systems and determines their likely percent contribution, and evaluates alternatives through programming, design, construction, operation, and retrofit (Crawley, 2010). In addition to the large amount of simulations EnergyPlus is capable of; it also performs algorithms from WINDOW 5 for more than 200 window types, heat and mass balance calculations, interior surface convection, moisture adsorption and desorption, thermal comfort, anisotropic sky models, advanced fenestration options and calculations, and daylighting illumination and controls. Another important feature of EnergyPlus is its ability to factor in weather conditions. Weather data inputs include location, data source, latitude, longitude, time zone, elevation, peak heating and cooling design conditions, holidays, daylight savings periods, and typical and extreme periods. All of the EnergyPlus output data files have easily interpreted formats such as spreadsheets, databases, or custom programs. Figure 3 explains the structure of the EnergyPlus simulation program. The Simulation Manager is the outermost program level followed by the underlying Heat and Mass Balance simulation and Building Systems simulation modules (Crawley et al., 2000).

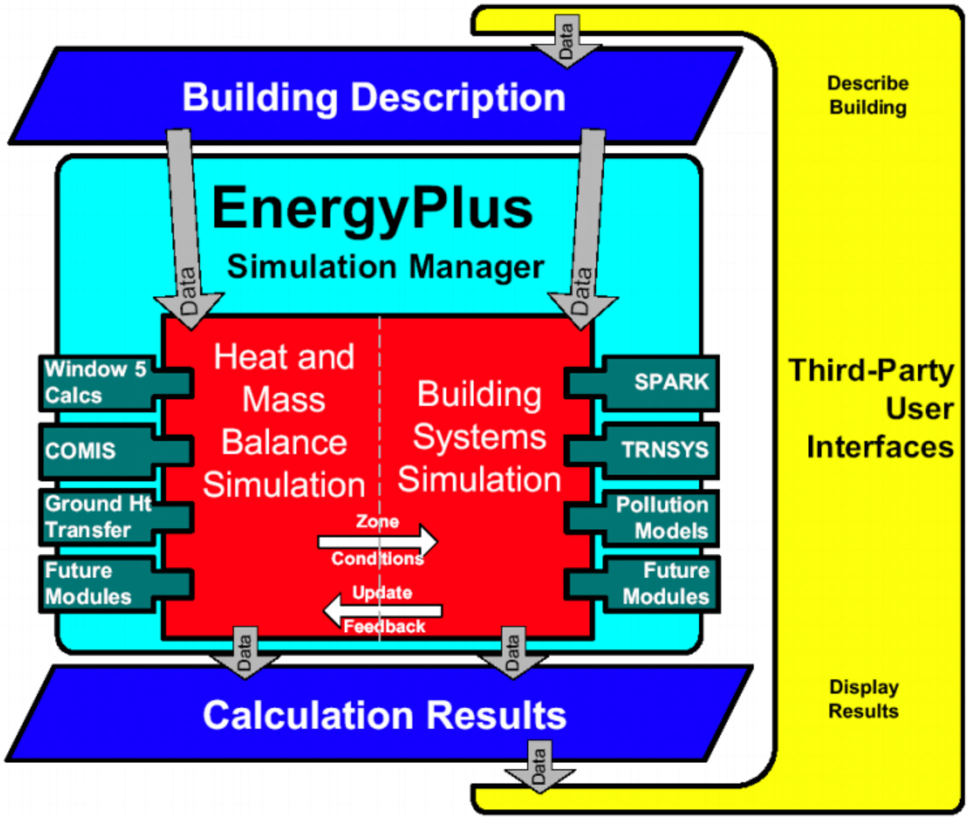

Figure 3: EnergyPlus simulation structure (Crawley et al., 2000)

Figure 4 shows the structure of the EnergyPlus simulation manager. This manager manages the meshing of the air heat balance module, surface heat balance module, and building systems simulation module. Outside and inside surface heat are calculated by the heat balance module. This includes the relationship between heat balance, boundary conditions, convection, radiation, and mass transfer. The air heat balance module accounts for air streams from ventilation, exhaust, and infiltration. Thermal mass of inter-zone airflow and direct convective heat gains are also analyzed by the air heat balance manager (Buhl et al., 2001).

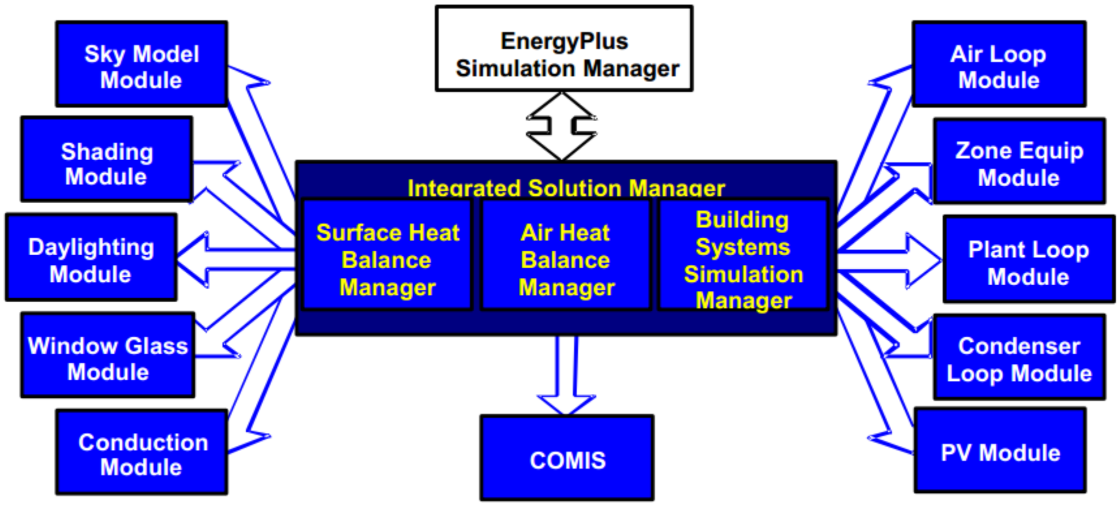

Figure 4: EnergyPlus simulation manager (Crawley et al., 2000)

2.5 OpenStudio Application Suite plug-in for Google SketchUp

To date, EnergyPlus is solely a simulation program without a graphical user interface (GUI) (Ibarra and Reinhart, 2009). Many independent developers have created third-party GUI's that mesh with EnergyPlus such as Simergy, CYPE CAD MEP, DesignBuilder, EFEN, AECOsim Energy Simulator and many more. Each GUI can serve individual purposes depending on the output need. For example, CYPE was created in order to design buildings in accordance to building codes from Spain, Portugal and France whereas DesignBuilder was created for building design analysis, LEED prerequisites and credit assessment, and calculating commercial building tax deductions in accordance with the United States Internal Revenue Service (IRS) (U.S. Department of Energy, 2013).

For the purposes of this project, the OpenStudio Application Suite plug-in for Google SketchUp was used. OpenStudio Application Suite was designed by the National Renewable Energy Laboratory (NREL) and was programmed around EnergyPlus in order to provide a supporting GUI interface for whole building energy modeling simulations (National Renewable Energy Laboratory). NREL created OpenStudio Application Suite in order to facilitate community development and private sector adoption (U.S. Department of Energy, 2013). The OpenStudio Application Suite includes standalone ParametricAnalysisTool, RunManager, and ResultsViewer. This program allows users to quickly assign attributes to geometry created in Google SketchUp by integrating Google Earth, Building Maker, and Photo Match. OpenStudio also allows the user to edit schedules, construction and material loads, spaces and zones, HVAC systems, service water heating designs, radiance, and visualizations. Additionally, the GUI allows ease in viewing EnergyPlus outputs in a graphical format making it more effortless to analyze information. In addition to ease of use, the GUI allows users to keep EnergyPlus simulations running and simultaneously view program outputs (National Renewable Energy Laboratory). Not only does OpenStudio Application Suite allow for an all-inclusive energy analysis but it is offered for free of charge by the NREL (U.S. Department of Energy, 2013).

2.6 Conclusion

The thermal properties of recycled demolition waste in masonry mortar applications have yet to be researched. Including these recycled materials in masonry mortar could contribute to more energy efficient and Zero Energy Buildings (ZEB). A thermal investigation in a building energy simulation program will expand industry knowledge of the thermal performance in a commercial building application.

CHAPTER 3: RESEARCH METHODOLOGY

The following chapter will detail the research methodology used to perform experimental testing and building energy simulations. A standard U.S. DOE strip mall model was used to analyze the thermal performance of recycled aggregates in mortar applications in concrete masonry construction. Analyses for the model were performed in seven locations recommended by the DOE based on varying climactic conditions across the United States. The work performed was similar to a previous graduate student at UNC Charlotte which used phase change materials (Peña 2012). Peña (2012) created a reference model using the same DOE reference model and EnergyPlus computer software for the phase change material research. Figure 5 shows a flow diagram of the research methodologies performed.

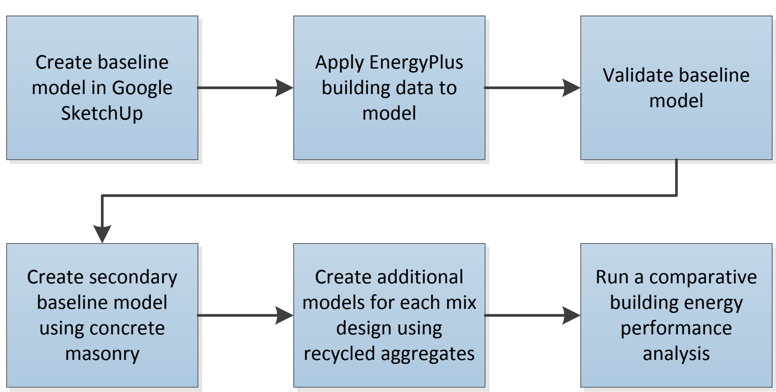

Figure 5: Flow diagram of research methodologies

3.1 Mortar Mix Design Material Development

To date there are six mortar mix designs that have been tested for adequate compressive strength. Testing the compressive strength before obtaining thermal data ensured that the mix designs were adequate for structural use. A consistent 1:3 ratio was used for the cement to aggregate ratio with the water and aggregate type varying. The six types of aggregates used in the mortar mix designs were C144 (reference sand), expanded slate, DBS (demolition brick sand), DB2, DB3, and DB4. ASTM C109 states that "water content for other cements is that sufficient to obtain a flow of 110 ± 5 (mm) in 25 drops of the flow table," however this only applies to cube testing. DBS was the initial demolition brick sand mortar mix created and DB2, DB3, and DB4 were the subsequent demolition brick sand mortar mixes created to address strength. Prisms and cubes were created to test the compressive strength for C144, expanded slate, and DBS so water was added to the mix until adequate workability was achieved. For the DB2, DB3, and DB4 mixes water was added until the mix was workable. The demolition brick sand aggregates, DBS had bonding complications during prism testing due to particle elongation preventing prescribed mortar joint height. As a result a new DBS mortar mix was created and DB4 was selected due to its strength being the highest of the series. Due to the controlled nature of laboratory testing, it should be noted that the mortar mixtures may vary in performance when exposed to different climate zones.

3.2 Specific Heat Capacity and Enthalpy Material Testing in Custom Mortar Mixes

Three mortar mixtures, C144, expanded slate, and DBS were tested for thermal performance over a varied spectrum of climactic conditions that masonry construction is typically exposed to in the United States. Thermal performance testing included specific heat capacity and thermal conductivity. Out of the three mortar mixtures only the most adequate mixtures were selected to replace the fine aggregate, C144. Adequate recycled aggregate mortar models were considered to be models that performed as well as or better than the lightweight and normal weight C144 mortar models. This replacement of fine aggregate promotes the use of industry recycled aggregates and waste materials in new construction. Lastly, a control group of mortar mixes using C144 sand in lightweight and normal weigh concrete masonry were also tested for consistency throughout.

The data for specific heat capacity in the mortar mixture was gathered using a differential scanning calorimeter (DSC). The DSC is a thermoanalytical technique that measures the difference in the amount of heat flow in a sample over a spectrum of varying temperatures which results in very precise test results. The temperature range was based on typical temperatures experienced by concrete masonry construction across the United States. The required DSC equipment was provided by UNC Charlotte's Materials Characterization Laboratory.

A TCi apparatus manufactured by C-Therm Technologies was used to gather thermal conductivity data for the mortar mixtures in a non-destructive manner. The effusivity of the mortar mixture was measured over a range of temperatures in order to obtain the thermal conductivity.

3.3 Reference Strip Mall Model in EnergyPlus™

The U.S. Department of Energy developed a database of sixteen commercial reference buildings across the United States which represent all U.S. climate zones and approximately 70% of the commercial building stock (National Renewable Energy Laboratory, 2011). These models were created as input files for EnergyPlus™ in order to coordinate research activities and create a common point of reference. The reference strip mall model that was used is available as new construction, existing buildings constructed post-1980, and existing buildings constructed pre-1980. The new construction model complies with the minimum requirements of American National Standards Institute (ANSI), American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE), and the Illuminating Engineering Society of North America (IESNA) Standard 90.1-2004 (ASHRAE 2004a), the post-1980 existing building model complies with the minimum requirements of Standard 90.1-1989 (ASHRAE 1989), and the pre-1980 model complies with older standards and studies performed in construction practices.

The reference model strip mall investigated in this study is a U.S. Department of Energy benchmark strip mall new construction mercantile building. Benchmark model proportions and store layout can be seen in Figure 6 and the same model is shown in Figure 7 in wire-frame. The building form required is a single story with an aspect ratio of 4.0 to 1.0, it houses ten stores with a total of 22,500 ft^2 (2,090 m^2), the floor-to-ceiling height is 17 ft (5.18 m), and has a glazing fraction of 0.11 (National Renewable Energy Laboratory, 2011). Out of the ten stores, eight are small measuring 25 feet by 75 feet and two are large measuring 50 feet by 75 feet. Overall, the entire strip mall building measures 300 feet by 75 feet. The south facing wall is the only glazed wall in the strip mall model including glass doors and windows. The north facing wall had typical exterior doors for rear store access. Building envelope construction for the concrete masonry strip mall models included fully grouted concrete masonry walls, a built-up flat roof with insulation above deck, and a slab-on-grade floor. The building envelope construction complies with ASHRAE Standard 90.1-2004. Concrete masonry walls also referred to as “mass walls” in EnergyPlus, must be defined as a wall with a heat capacity exceeding 7 BTU/ft^2 ˚F (143 MJ/m^2 ˚C) or 5 BTU/ft^2 ˚F (102 MJ/m^2 ˚C) with a material weight no greater than 120 lb/ft^3 (4.7 GJ/m^3). Roof construction included a typical built-up roof including a roof membrane, non-resolution roof insulation, and metal decking.

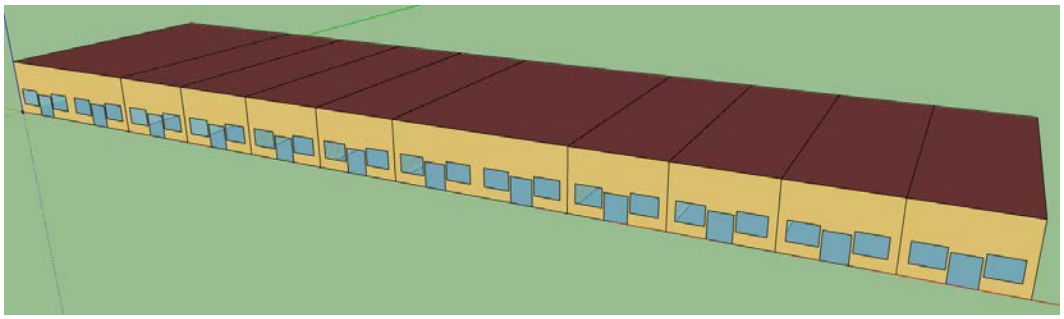

Figure 6: Solid benchmark model exterior view

Figure 7: Wireframe benchmark model interior view

3.4 Creating a Concrete Masonry Reference Model in EnergyPlus

Creating a concrete masonry reference model in EnergyPlus using the strip mall reference model was the first step in inserting the recycled aggregate mortar materials. By creating a concrete masonry model based on the DOE reference model accurate energy use values were generated. EnergyPlus allows developers and software users to easily insert the new building materials. For this study the reference model provided by the DOE was created using EnergyPlus version 7.2, however the current version of EnergyPlus being used for simulation is 8.1.0. Due to the difference in software versions the IDF file was updated using the EnergyPlus IDF Version Updater in Figure 8.

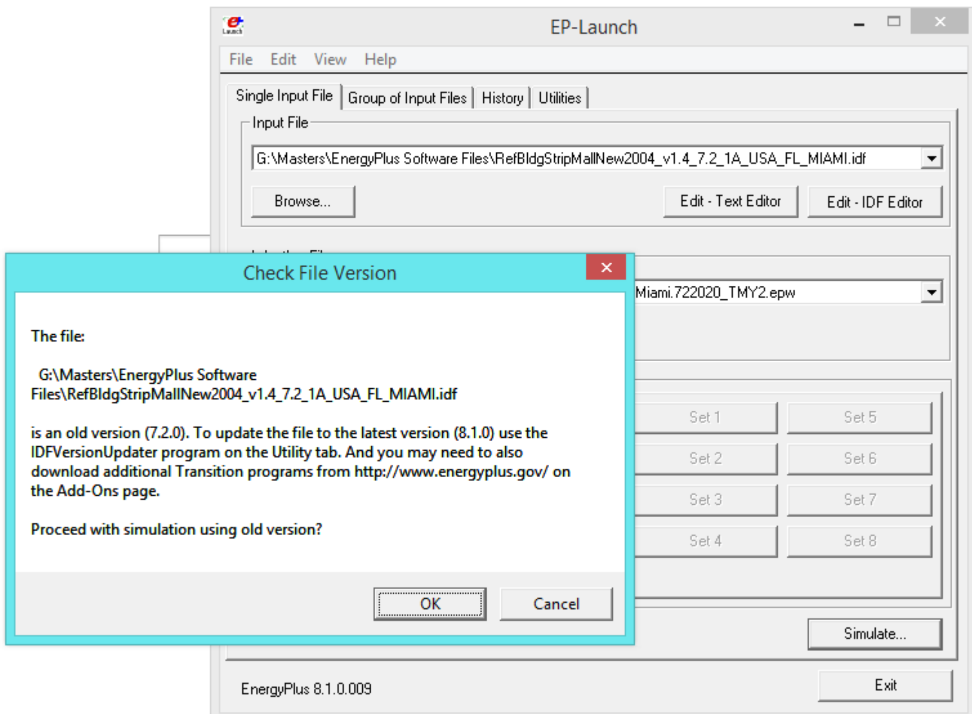

Figure 8: EnergyPlus IDF Version Updater

Next, the building envelope had to be changed from steel framed to concrete masonry with the EnergyPlus IDF Editor. The concrete masonry material data was obtained from a predefined EnergyPlus IDF file with building materials from ASHRAE 2005 Handbook – Fundamentals. Lightweight and normal weight concrete block building envelope materials were imported into the original reference model. These two building materials can be seen in Figure 9.

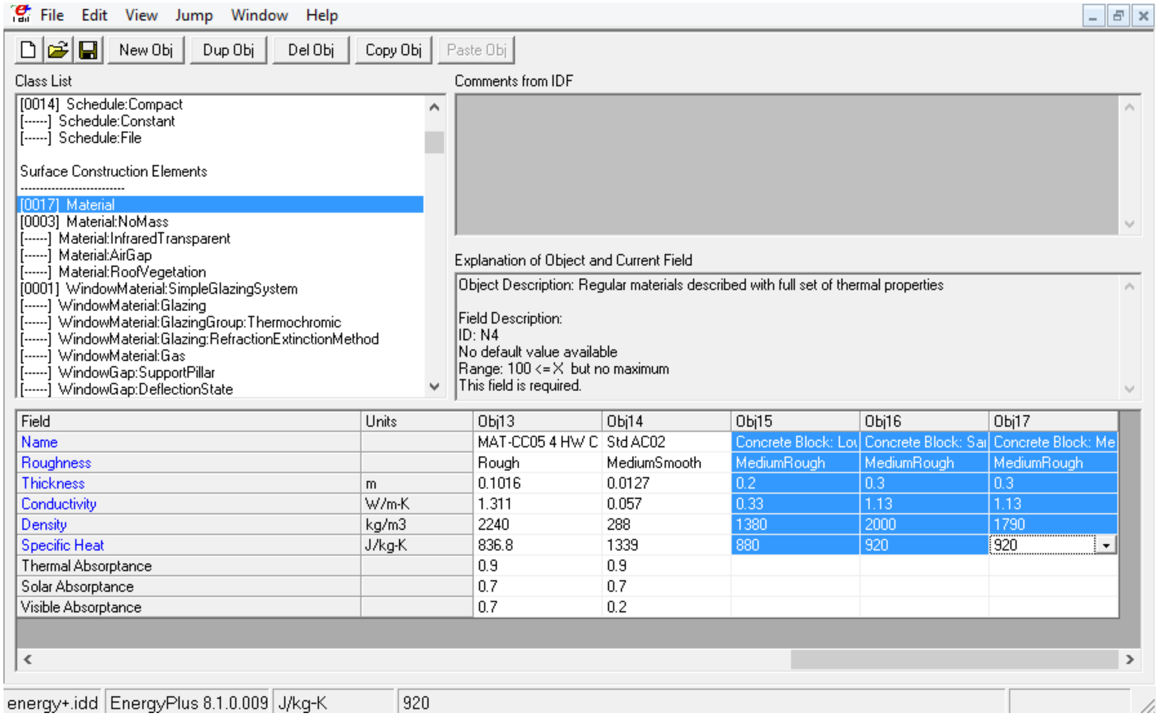

Figure 9: Importing concrete masonry into reference model

Once the materials were imported the building envelope was redefined. Previously the reference building exterior envelope from exterior to interior consisted of wood siding, steel frame non-residential wall insulation, and ½ inch gypsum. The construction of the concrete masonry wall was obtained by generating an example model from the EnergyPlus Example File Generator (EEFG). The Example File Generator is a streamlined online version of EnergyPlus that allows the user to generate an EnergyPlus model with very basic options (U.S. DOE, 2013). Figure 10 shows the website used to generate the concrete masonry example file. Concrete masonry building envelope construction from exterior to interior consists of 1 inch of stucco, 8 inch concrete block (lightweight and normal weight with C144 mortar), and ½ inch gypsum.

The concrete masonry building envelope was copied from the example file IDF and inserted into the envelope construction tab in EnergyPlus. A building envelope was created for lightweight and normal weight concrete masonry construction using C144 mortar.

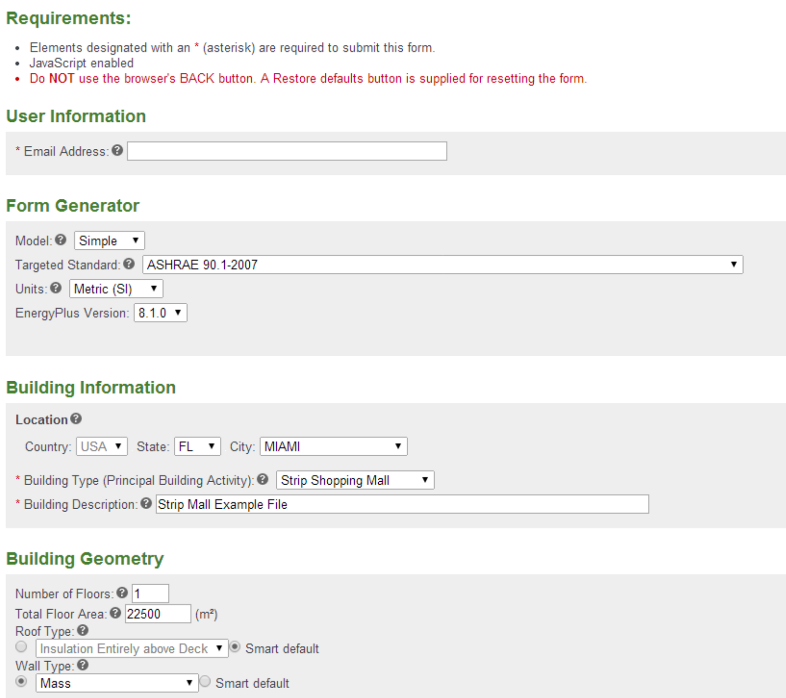

Figure 10: EnergyPlus Example File Generator

The final step in replacing the steel construction with concrete masonry construction was to replace the selected exterior walls in the “BuildingSurface Detailed” tab. This step allowed for detailed entry of building heat transfer surfaces. The highlighted row in Figure 11 shows the wall construction selection process.

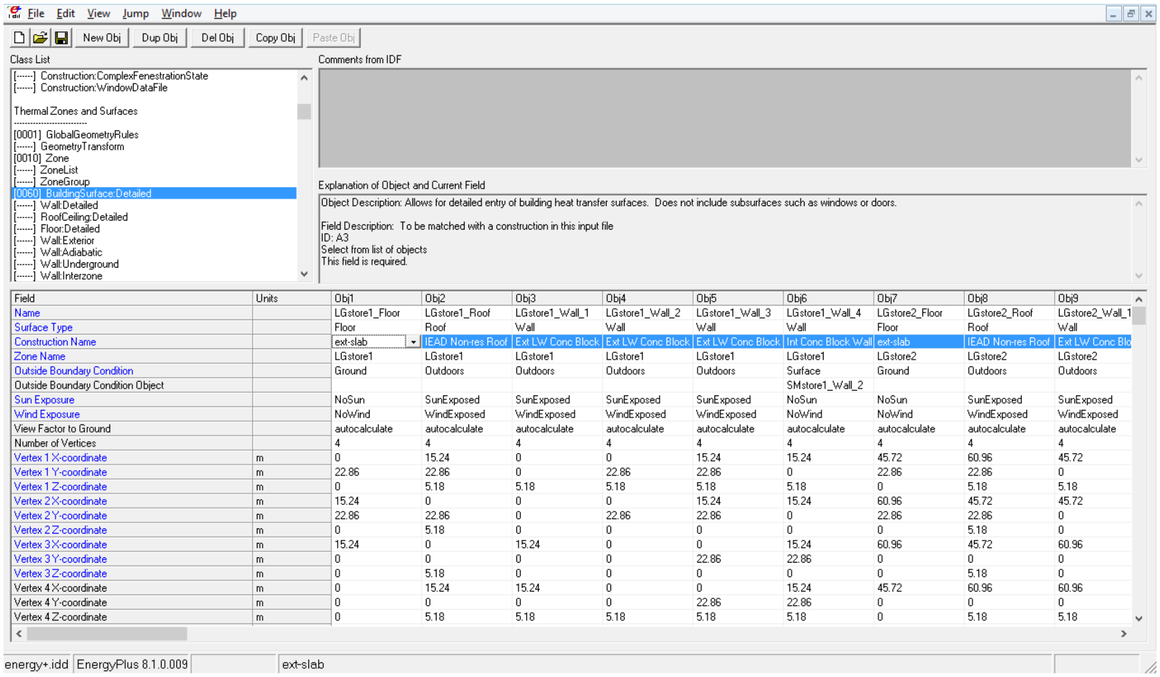

Figure 11: EnergyPlus heat transfer surface selection

The thermal performance data gathered for specific heat capacity and thermal conductivity for each mortar mix design was entered into an EnergyPlus strip mall model and compared to a typical United States benchmark model. A data-based analysis was then performed between the seven models and a conclusion was made based on whether the recycled aggregates used in the mortar mix design were comparable to those of virgin aggregates. The data analysis performed determined whether or not recycled aggregates are a more energy efficient option than raw virgin aggregates.

3.5 Strip Mall Building Model Locations

An accurate building energy simulation requires that the reference model be tested in many different climactic conditions to understand how the new materials perform in varying environments. For this investigation concrete masonry building envelope construction with recycled aggregate thermal properties were tested in cold, warm, and hot climate conditions.

The DOE, ASHRAE, and the International Energy Conservation Code (IECC) developed a climate zone map dividing the United States into eight zones that assist builders and designers in determining the appropriate climate classification (U.S. DOE, 2010). Figure 12 shows seven of the eight climate zones by color and county. These eight zones are divided according to temperature and are further separated into moisture-oriented classifications A (moist), B (dry), and C (marine). The climate zone map allows for a total of 24 climate classifications across the United States. These eight climate zones and letters determined by the IECC are used by ASHRAE standards for building compliance in respect to ASHRAE 90.1-2004.

For this investigation, a building energy simulation was performed in seven of the eight climate zones across the United States. The seven building simulations were performed in Miami, FL (Zone 1A), Phoenix, AZ (Zone 2B), Los Angeles, CA (Zone 3B), Baltimore, MD (Zone 4A), Seattle, WA (Zone 4C), Boulder, CO (5B), and Minneapolis, MN (Zone 6A). All of these locations were recommended for energy simulation programs by the DOE due to the overwhelming amount of location options (Crawley, 1998). Denver, CO and New York, New York were recommended cities for these simulations but were replaced with Boulder, CO and Baltimore, MD based on the DOE reference models available. Despite the change in the two cities, the IECC climate zone classifications remain the same. Figure 13 shows a map of the United States and the location of each of the cities indicated with a star.

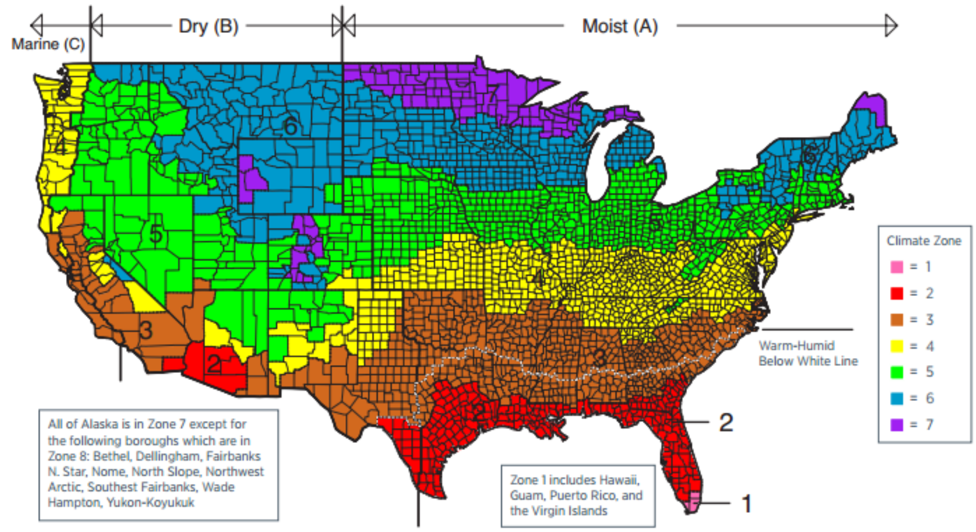

Figure 12: IECC climate zone map (U.S. DOE 2010)

Figure 13: Energy simulation locations (Graphic Maps)

CHAPTER 4: RESULTS AND DISCUSSION

The following chapter discusses and compares the results generated in EnergyPlus™ for the DOE reference strip mall model, the lightweight concrete block model, and the normal weight concrete block model. The performance of both the lightweight model and the normal weight model were investigated with recycled brick masonry aggregate and expanded slate aggregate mortars. Overall, building energy simulations were performed for the DOE reference model, lightweight C144 model, lightweight RBMA model, lightweight expanded slate model, normal weight C144 model, normal weight RBMA model, and normal weight expanded slate model. To understand the performance of the DOE reference building envelope, two C144 building envelopes, and the four recycled aggregate mortar building envelopes, each model was examined in different IECC climate zones across the United States. These locations include Miami, Boulder, Los Angeles, Minneapolis, Baltimore, Phoenix, and Seattle. Each of the concrete masonry models were created based on the validated DOE reference strip mall model for accuracy. A total of seven models were simulated in seven locations for a total of 49 models.

After the reference strip mall model was validated against results provided by the DOE, the fully grouted lightweight and normal weight concrete masonry with C144 mortar building envelopes were substituted for the basic steel frame envelope. Annual consumptions for heating, ventilation, and air conditioning (HVAC), building end-use annual energy consumption, and total facility annual utility costs are discussed.

4.1 Strip Mall Model Lighting

It should be noted that lighting accounts for a significant portion of the entire building energy consumption. Using the building area method or space-to-space method defined in ASHRAE Standard 90.1-2004, the lighting power densities (LPDs) for new construction are calculated. The strip mall LPDs were divided into three levels: high with two stores, medium with three stores, and low with five stores. The mixed lighting intensities used in the energy simulations are based on research performed by Liu et al. (2006). Table 1 shows the LPD levels and the pertaining ASHRAE Standard 90.1-2004 table.

Table 1: DOE reference building lighting assumptions (NREL, 2011)

Building Type	New Construction Models (ASHRAE 90.1-2004)
Strip Mall	2 Stores: 2.23 W/ft^2 (24 W/m^2) (Table 9.6.1 retail plus accent lighting)
	3 Stores: 1.7 W/ft^2 (18.3 W/m^2) (Table 9.6.1 retail)
	5 Stores: 1.28 W/ft^2 (13.8 W/m^2)

4.2 Data Presentation of Weekly Summary for Heating and Cooling Energy Consumption

Energy consumption for peak winter and summer weather was analyzed for the first week of January and the first week of July for all seven model locations. These weeks represent the most severe temperatures experienced throughout the year. The heating and cooling hourly analyses were performed separately for a comparison of lightweight model results to DOE reference model results and normal weight model results to DOE reference model results. An example of the hourly values plotted is displayed in Figure 14. The largest difference in energy consumption is seen during the middle portion of the day. Each day is indicated on the graph by the date and time beginning at 1:00 AM. Due to the same variation of hourly energy differences, the results were compared as a function of weekly total energy use given by Table 2. The remaining graphs are displayed in Appendix A. A clearer method to display the data is shown in Table 2. The negative percentage indicates a decrease in energy efficiency whereas, a positive percentage indicates an increase in energy efficiency.

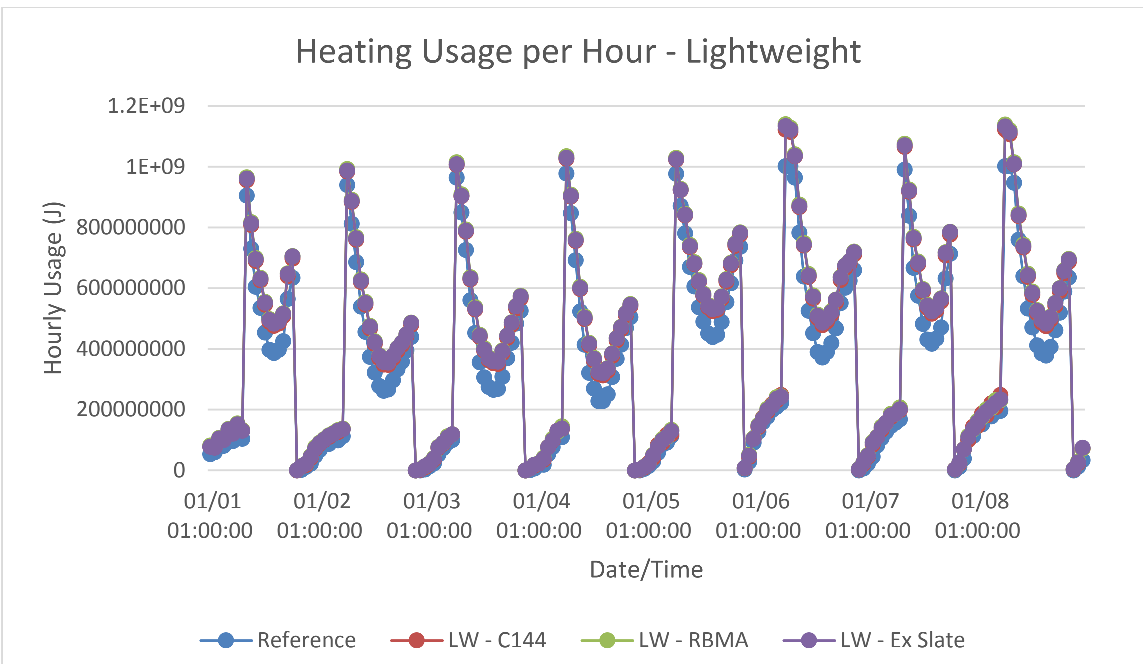

Figure 14: Boulder, CO heating usage per hour for lightweight concrete masonry models example graph

Table 2: Boulder, CO heating energy usage week summary example table

Heating:Gas Week Sum (January 1st - January 8th) - Boulder							
	Reference	LW - C144	LW - RBMA	LW - Ex Slate	NW - C144	NW - RBMA	NW - Ex Slate
Total (GJ):	67.727	77.840	79.117	78.646	93.236	93.114	92.936
Hours Operating:	183	188	189	189	192	192	192
Percent Diff:		-14.93%	-16.82%	-16.12%	-37.66%	-37.48%	-37.22%

4.3 Miami, Florida

4.3.1 Miami, FL Reference Strip Mall Building Energy Consumption

Miami, Florida is classified as Zone 1A, hot-humid, by the IECC climate zone maps. Hot-humid is defined by the DOE as "a region that receives more than 20 inches (50 cm) of annual precipitation," (U.S. DOE, 2010). Another required condition is that the temperature must be greater than 67°F (19.5°C) or higher for 3,000 or more hours during the warmest six consecutive months of the year or the temperature must remain greater than 73°F (23°C) or higher for 1,500 or more hours during the warmest six consecutive months of the year.

Figures 15, 16, and 17 show the annual percentage of energy consumption by category for the reference strip mall model, lightweight C144 concrete masonry model, and the normal weight C144 concrete masonry model respectively. Interior lighting is the largest consumer of energy for all three models. The only variances are in the heating (natural gas), cooling, and fan usage.

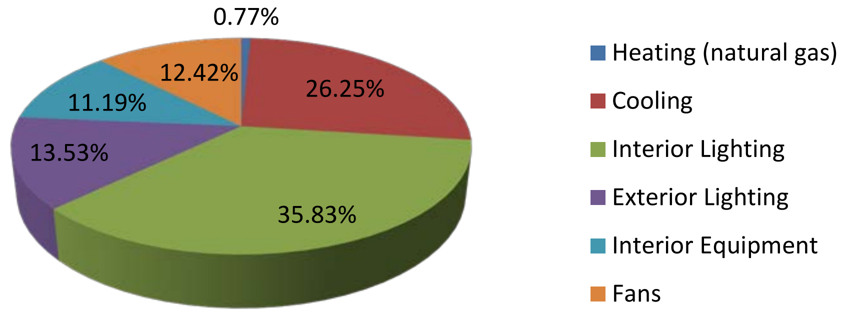

Figure 15: Miami, FL strip mall DOE reference model annual energy consumption by end-use

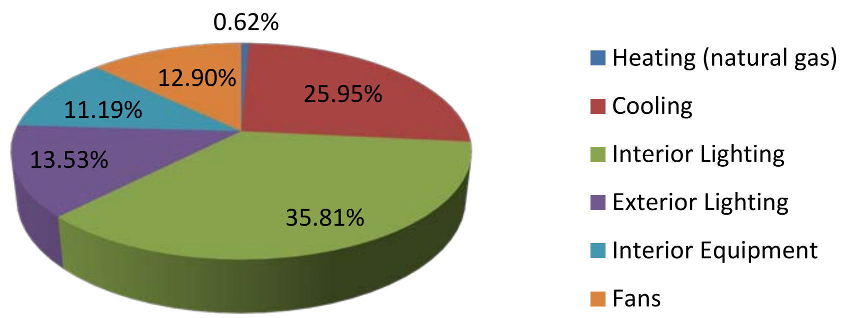

Figure 16: Miami, FL strip mall lightweight C144 concrete masonry model annual energy consumption by end-use

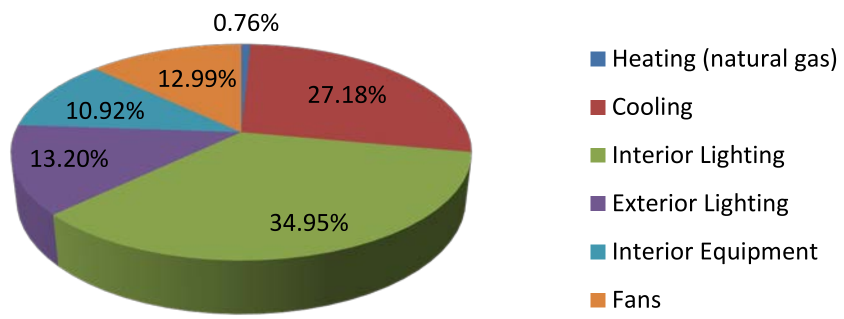

Figure 17: Miami, FL strip mall normal weight C144 concrete masonry model annual energy consumption by end-use

4.3.2 Miami, Florida Strip Mall Building End-Use Performance with Recycled Aggregate Mortar

Figures 18, 19, 20, and 21 show the end-use energy consumption for lightweight RBMA, lightweight expanded slate, normal weight RBMA, and normal weight expanded slate mortar models respectively. Like the baseline models for Miami, the main source of end-use energy consumption is the interior lighting. Slight variations in heating (natural gas), cooling, and fan energy usage can be observed.

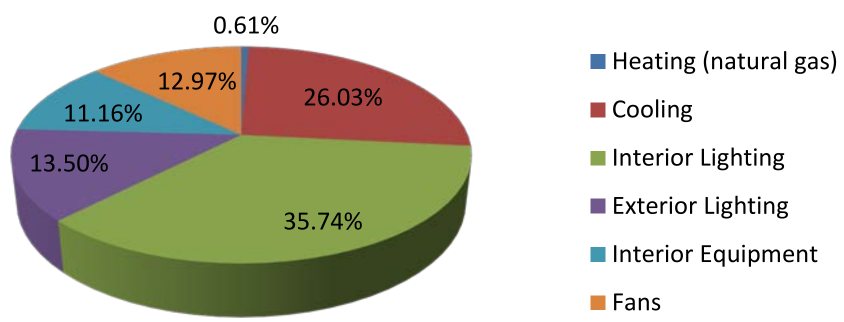

Figure 18: Miami, FL strip mall lightweight concrete masonry model with RBMA mortar annual energy consumption by end-use

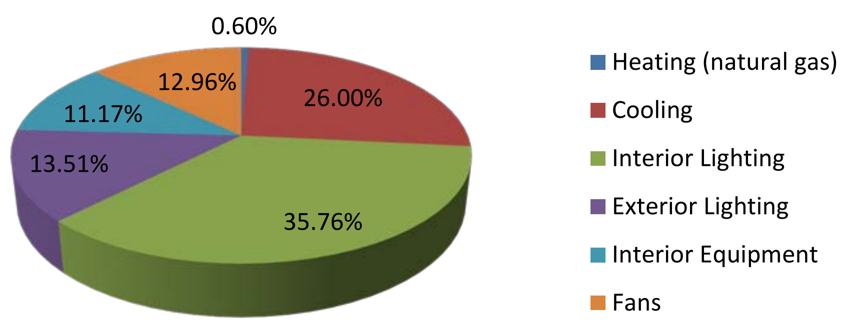

Figure 19: Miami, FL strip mall lightweight concrete masonry model with expanded slate mortar annual energy consumption by end-use

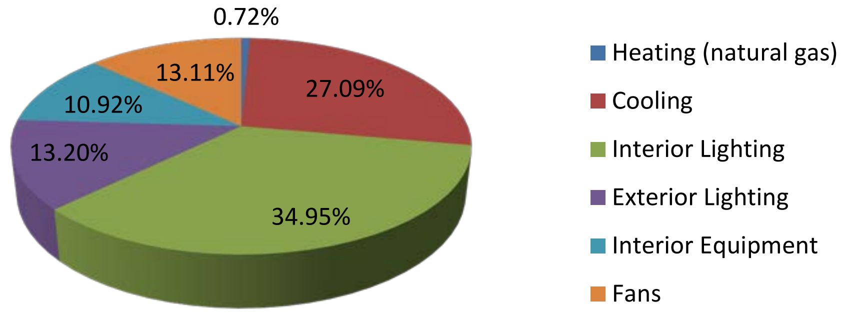

Figure 20: Miami, FL strip mall normal weight concrete masonry model with RBMA mortar annual energy consumption by end-use

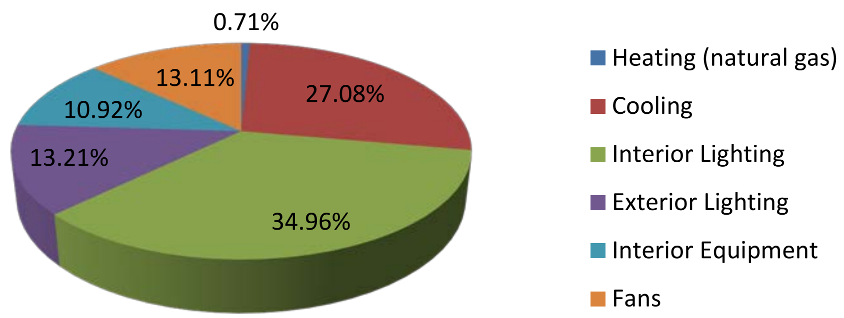

Figure 21: Miami, FL strip mall normal weight concrete masonry model with expanded slate mortar annual energy consumption by end-use

Table 3 compares the change in percentage between the concrete masonry strip mall lightweight C144 model, normal weight C144 model, and the four recycled aggregate variations to the DOE reference model. An energy efficiency decrease of 0.04% for the lightweight C144 model was the most notable change in percent difference between the three lightweight models and the DOE reference model. The energy usage for the lightweight C144 model has an energy efficiency increase of 19.83% for heating (natural gas), increase of 1.10% for cooling, and 3.90% decrease in fans. Despite the large increase in heating efficiency, the total efficiency does not increase very much. This is due to the heating only accounting for a total of 0.62% of the entire end-use energy consumption. The lightweight RBMA model and lightweight expanded slate model decreased in energy efficiency by 0.26% and 0.19%, respectively.

All three normal weight models vary little from one another in the total amount of energy consumption. The normal weight C144 and RBMA models both decrease 2.50% in energy efficiency and the normal weight expanded slate model decreases 2.47% in energy efficiency. Even though there is very little deviation between the three models, the normal weight expanded slate model still out performed the other materials. Overall, heating (natural gas) increased 4.96%, cooling decreased 5.71%, and fan usage decreased 8.14% in energy efficiency compared to the DOE reference model.

Any of the lightweight models would be a suitable replacement for the DOE steel-frame reference model; however, the best performance was the lightweight C144 model. In comparison to the lightweight C144 model the normal weight expanded slate model would be a poor option to replace the typical steel framing of the DOE reference model.

Table 3: Miami, FL strip mall annual building utility performance summary

Energy End-Use	U.S. DOE Reference Model	Lightweight - C144 (< 105 lb/ft^3)		Lightweight - RBMA (< 105 lb/ft^3)		Lightweight - Ex Slate (< 105 lb/ft^3)		Normal Weight - C144		Normal Weight - RBMA (> 125 lb/ft^3)		Normal Weight - Ex Slate (> 125 lb/ft^3)	
	Energy (GJ)	Energy (GJ)	% Diff	Energy (GJ)	% Diff	Energy (GJ)	% Diff	Energy (GJ)	% Diff	Energy (GJ)	% Diff	Energy (GJ)	% Diff
Heating (natural gas)	10.29	8.25	19.83%	8.12	21.09%	8.04	21.87%	10.41	-1.17%	9.8	4.76%	9.78	4.96%
Cooling	350.55	346.7	1.10%	348.50	0.58%	347.78	0.79%	371.96	-6.11%	370.83	-5.79%	370.55	-5.71%
Interior Lighting	478.41	478.41	0.00%	478.41	0.00%	478.41	0.00%	478.41	0.00%	478.41	0.00%	478.41	0.00%
Exterior Lighting	180.72	180.72	0.00%	180.72	0.00%	180.72	0.00%	180.72	0.00%	180.72	0.00%	180.72	0.00%
Interior Equipment	149.43	149.43	0.00%	149.43	0.00%	149.43	0.00%	149.43	0.00%	149.43	0.00%	149.43	0.00%
Fans	165.9	172.37	-3.90%	173.59	-4.64%	173.43	-4.54%	177.76	-7.15%	179.47	-8.18%	179.4	-8.14%
Total	1335.3	1335.88	-0.04%	1338.77	-0.26%	1337.81	-0.19%	1368.69	-2.50%	1368.66	-2.50%	1368.29	-2.47%

An hourly heating and cooling analysis was performed in EnergyPlus for heating and cooling usage over peak temperature weeks for winter and summer. The heating and cooling hourly analyses were performed separately for a comparison of the lightweight models to the DOE reference model results and the normal weight models to the DOE reference model results. Hourly data was then combined to report total energy use for the two critical weeks.

Heating usage values per hour for the first week of January are displayed in Table 4 for the DOE reference model and the concrete masonry models. Due to the hot-humid climate in Miami, heat is only used for a few hours out of the coldest week of the year.

Table 4: Miami, FL heating energy usage week summary

Heating:Gas Week Sum (January 1st - January 8th) - Miami							
	Reference	LW - C144	LW - RBMA	LW - Ex Slate	NW - C144	NW - RBMA	NW - Ex Slate
Total (GJ):	2.065	2.013	2.021	2.005	2.495	2.431	2.425
Hours Operating:	15	15	15	15	21	21	21
Percent Diff:		2.52%	2.11%	2.89%	-20.82%	-17.71%	-17.45%

The use of heat between the lightweight C144 model and the lightweight recycled aggregate mortar models remains consistent with the number of hours the heat operated. The heat operated for a total of fifteen hours from January 1st to January 8th for the lightweight models. Even though the lightweight models operated the same number of hours, the DOE reference model consumed a total of 2.065 GJ which is higher than any of the lightweight models. The lightweight C144, lightweight RBMA, and lightweight expanded slate models consumed 2.013 GJ, 2.021 GJ, and 2.005 GJ. One model that deviated from the rest is the expanded slate model. The lightweight expanded slate model appears to behave differently in cooler temperatures and consumes a significantly lower amount of energy than the lightweight C144 model. A 2.52% increase in energy efficiency was experienced between the lightweight C144 model and the DOE reference model. Both the RBMA and expanded slate lightweight models experienced increases in energy efficiency at 2.11% and 2.89% respectively. Although only slightly, the lightweight expanded slate model outperformed the lightweight C144 model.

The normal weight concrete masonry models performed differently than the lightweight concrete masonry models. The heat operated for a total of twenty-one hours over eight days in contrast to the fifteen hours over eight days for the DOE reference model and the lightweight models. This created a large difference in the amount of energy consumed through the peak winter week. All of the normal weight model hourly consumption results were roughly around the same. 2.495 GJ were consumed for the normal weight C144 model, 2.431 GJ were consumed for the normal weight RBMA model, and 2.425 GJ were consumed for the expanded slate model. These values are approximately 0.400 GJ greater than the DOE reference model. A 20.82% decrease in energy efficiency was experienced from the DOE reference model to the normal weight C144 model. Even though the normal weight C144 model performed poorly, the normal weight RBMA and expanded slate models performed slightly better. The energy efficiency decreased by 17.71% for the normal weight RBMA model and by 17.45% for the normal weight expanded slate model.

Based on the analyses on heating energy consumption between the lightweight, normal weight, and DOE reference models, the normal weight models performed poorly. The lightweight models consume less energy than the DOE reference model with the lightweight expanded slate consuming the least amount of energy. Furthermore, both the expanded slate concrete masonry models performed better than the respective concrete masonry models.

Cooling usage summaries for the first week of July are displayed in Table 5 for the DOE reference model and the concrete masonry model variations. Due to the hot-humid climate in Miami, cooling systems were running for the majority of the day during the warmest month of the year.

Table 5: Miami, FL cooling energy usage week summary

Cooling:Electricity Week Sum (July 1st - July 8th) - Miami							
	Reference	LW - C144	LW - RBMA	LW - Ex Slate	NW - C144	NW - RBMA	NW - Ex Slate
Total (GJ):	10.560	10.637	10.705	10.683	11.384	11.370	11.362
Hours Operating:	109	109	109	109	109	109	109
Percent Diff:		-0.73%	-1.38%	-1.17%	-7.80%	-7.67%	-7.60%

The lightweight C144 model and the lightweight recycled aggregate mortar models remained consistent with the amount of energy used for cooling and the number of hours the cooling system was operating. The lightweight models consumed 10.637 GJ for the C144 model, 10.705 GJ for the RBMA model, and 10.683 GJ for the expanded slate model. Cooling energy consumption for the DOE reference model was only 10.560 GJ and operated for a total of 109 hours from January 1st through January 8th. Like the DOE reference model, the lightweight concrete masonry models' cooling systems also ran for a total of 109 hours over the same time period. In comparison to the DOE reference model, the lightweight C144, lightweight RBMA, and lightweight expanded slate models decreased in energy efficiency by 0.73%, 1.38%, and 1.17% respectively.

Out of the three lightweight concrete masonry models, the C144 model performed the best.

The normal weight models consumed approximately 0.5 GJ more while cooling than the lightweight models. Half a gigajoule means that there is a larger energy gap between the DOE reference model and the normal weight models. The normal weight models consumed 11.384 GJ for the C144 model, 11.370 GJ for the RBMA model, and 11.362 GJ for the expanded slate model. Even though the weekly sum of the cooling energy consumption is higher for the normal weight models, the number of hours required to cool the facility remained at 109 hours. A 7.80% decrease in energy efficiency was seen from the DOE reference model to the normal weight C144 model. The normal weight expanded slate and RBMA models also decreased in energy consumption but by slightly less at 7.67% and 7.60%.

Both the lightweight models and the normal weight models exceed the energy usage of the DOE reference model for cooling. Although the energy consumption is greater, it only exceeds the DOE reference model by a very small amount. Miami, Florida experiences intense summer temperatures and requires a large amount of energy for cooling. The normal weight models consume more energy but the normal weight recycled aggregated variations outperform the normal weight C144 model. The DOE reference model or lightweight concrete masonry models would be a suitable energy efficient choice based on these results.

An energy consumption analysis was performed for fan usage during the winter and summer. Figure 22 displays the fan energy consumption for a peak week during both seasons. These peak weeks are from January 1st to January 8th and July 1st to July 8th.

During the winter, fan energy consumption is much higher than the fan energy consumption during the summer. The percent difference in the fan energy consumption during summer versus winter is consistently 3.60%. Interestingly, the fan energy consumption is consistent during the winter and summer peak weeks.

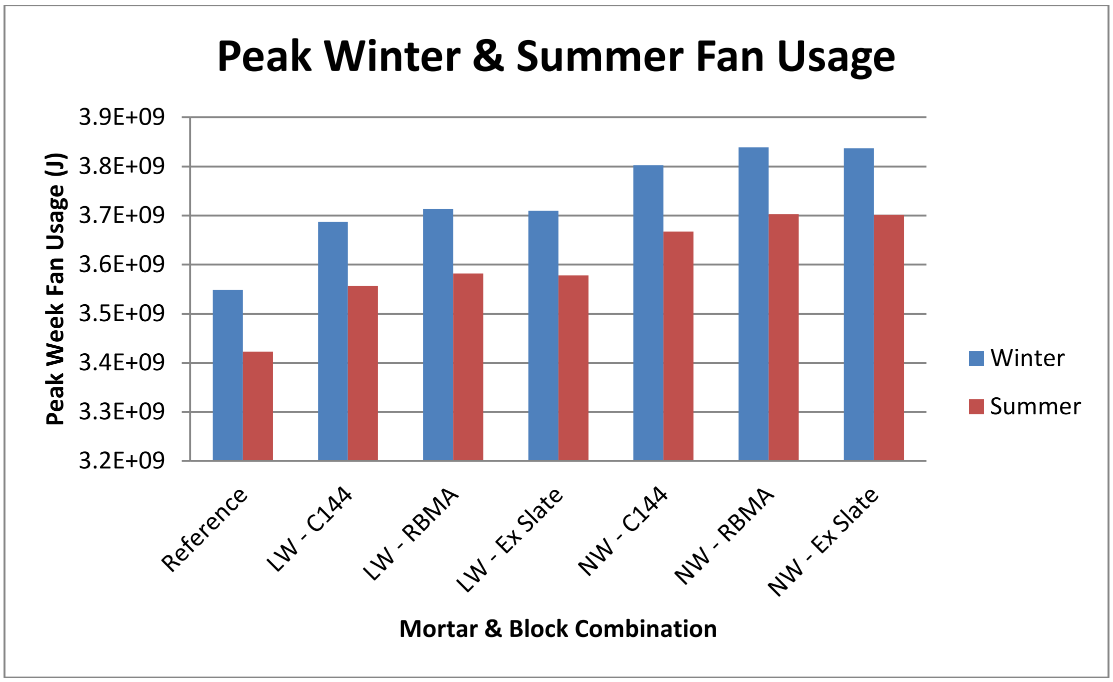

Figure 22: Miami, FL strip mall concrete masonry fan usage for peak summer and winter times

4.4 Boulder, Colorado

4.4.1 Boulder, CO Reference Strip Mall Building Energy Consumption

Boulder, Colorado is classified as Zone 5B by the IECC climate zone map. This means that the climactic conditions are cold-dry (U.S. DOE, 2010). A cold climate is defined as a region that has between 5,400 and 9,000 heating degree days (65°F). Cold is used to describe both zones 5 and 6. The letter “B” is what indicates the humidity level as dry.

Figures 23, 24, and 25 show the overall energy usage by percentage for the DOE reference strip mall model, lightweight C144 concrete masonry model, and normal weight C144 concrete masonry model. Like the previous model, lighting consumes a large portion of the energy usage in all three models; however, heating is the largest consumer of energy ranging from 44.96% (C144) to 51.12% (normal weight) of the overall energy usage. The need for a large amount of heat is consistent with the cold-dry climactic conditions. In contrast, cooling consumes the least amount of energy ranging from 2.24% (lightweight) to 2.63% (C144). This is due to cold temperatures year round.

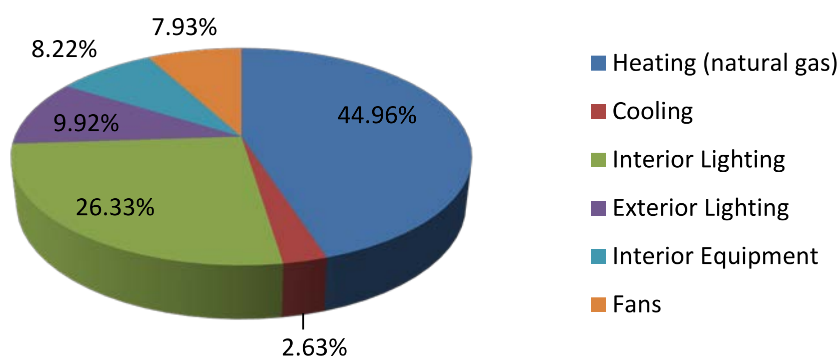

Figure 23: Boulder, CO strip mall DOE reference model annual energy consumption by end-use

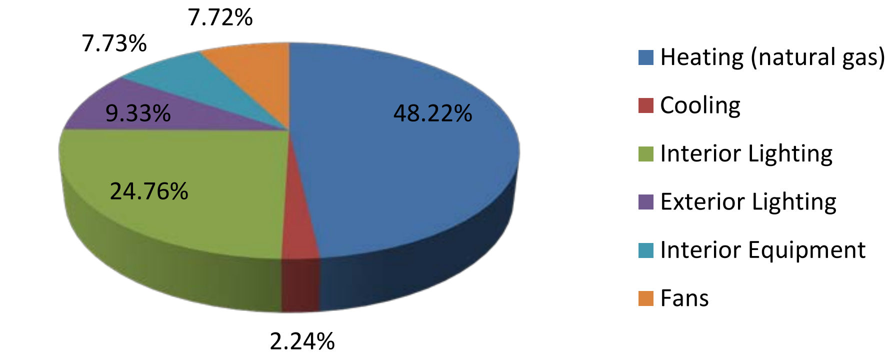

Figure 24: Boulder, CO strip mall lightweight C144 concrete masonry model annual energy consumption by end-use

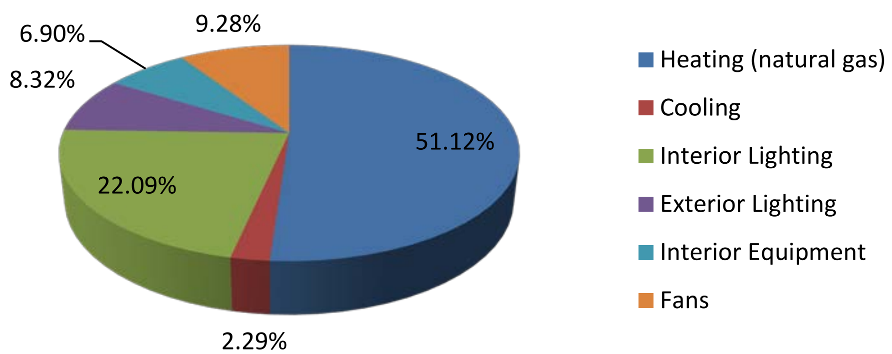

Figure 25: Boulder, CO strip mall normal weight C144 concrete masonry model annual energy consumption by end-use

4.4.2 Boulder, CO Strip Mall Building End-Use Performance with Recycled Aggregate Mortar

End-use energy consumption for the lightweight RBMA, lightweight expanded slate, normal weight RBMA, and normal weight expanded slate models are shown in Figures 26, 27, 28, and 29. For the lightweight RBMA and the lightweight expanded slate models the heating usage remains the highest consumer of energy at 48.50% and 48.40% respectively. These values increased from 48.22% for the C144 lightweight model. Lighting energy consumption remained the second largest consumer of energy for the

Boulder, CO recycled aggregate models. Overall, the lightweight models deviated less than one percent in energy consumption for each end-use category. The normal weight RBMA and normal weight expanded slate models performed similarly to the lightweight models; however, the heating energy consumption was slightly higher. These values are 51.12% (normal weight C144), 51.06% (normal weight RBMA), and 51.03% (normal weight expanded slate). Like the lightweight models, the lighting for the normal weight recycled aggregate models remain within a one percent deviation from the normal weight C144 model consumption of 22.09%.

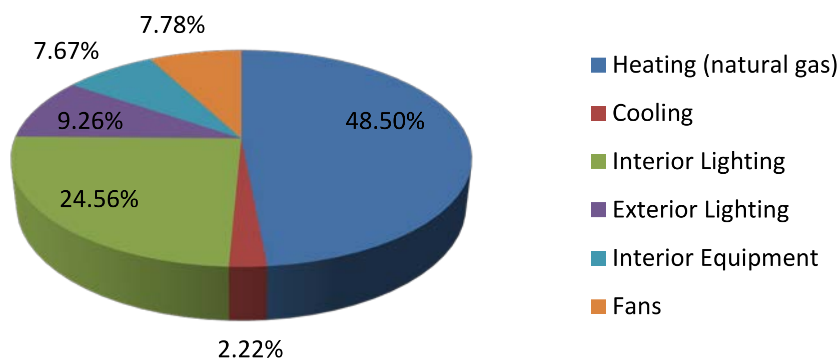

Figure 26: Boulder, CO strip mall lightweight concrete masonry model with RBMA mortar annual energy consumption by end-use

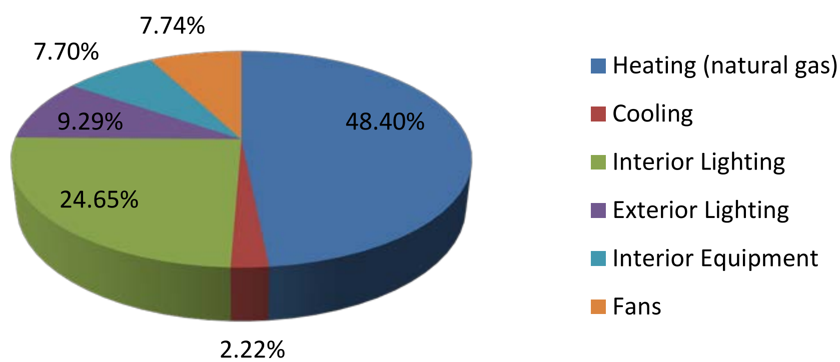

Figure 27: Boulder, CO strip mall lightweight concrete masonry model with expanded slate mortar annual energy consumption by end-use

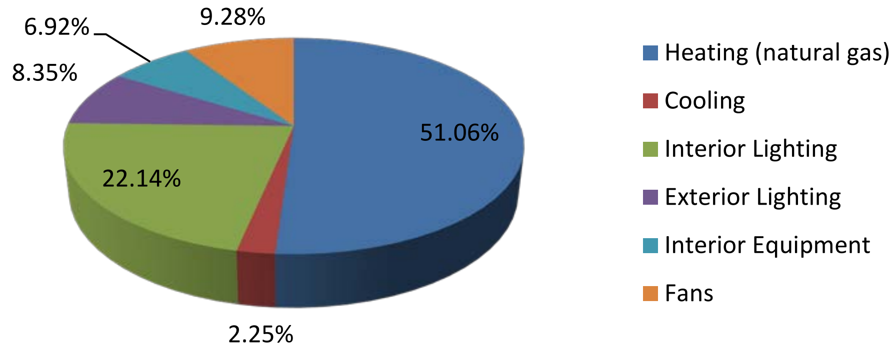

Figure 28: Boulder, CO strip mall normal weight concrete masonry model with RBMA mortar annual energy consumption by end-use

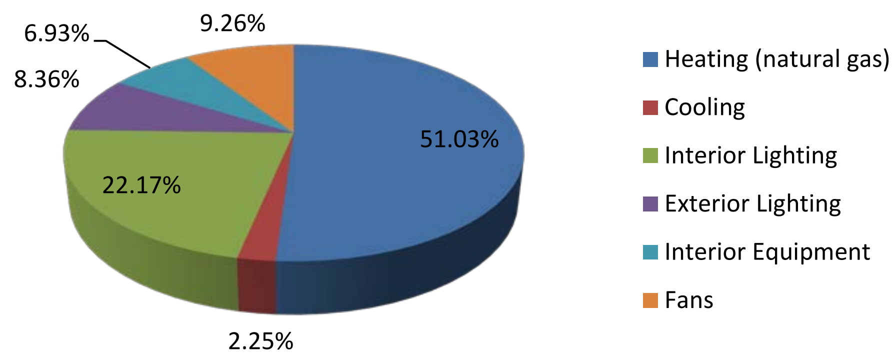

Figure 29: Boulder, CO strip mall normal weight concrete masonry model with expanded slate mortar annual energy consumption by end-use

Table 6 displays the difference in percentages between the DOE reference, lightweight C144, lightweight recycled aggregate mortar, normal weight C144, and normal weight recycled aggregate mortar models. The energy efficiency for the lightweight C144 model is 6.34% less energy efficient than the DOE reference model. The lightweight C144 model has an energy efficiency decrease of 14.03% for heating (natural gas), increase of 9.57% for cooling, and decrease of 3.56% for fans. The lightweight RBMA model and lightweight expanded slate model have a lower energy efficiency. These energy efficiencies are equal to a decrease of 7.19% and 6.80%

respectively. Both of these consume a significantly higher amount of energy than the lightweight C144 model and can be disregarded for the purpose of substituting the basic steel framing material of the DOE reference model.

The most suitable model from the normal weight models would be the expanded slate, decreasing in energy efficiency by 18.75% more energy than the DOE reference model. The normal weight RBMA model decreased by 18.91% and the normal weight C144 model decreased by 19.21%. Overall, the normal weight expanded slate model has an energy efficiency decrease of 34.78% for heating, a decrease of 1.61% for cooling, and a decrease of 38.70% for fan energy consumption. All of these amount to a total of an 18.75% decrease in energy efficiency.

Both the lightweight C144 and normal weight expanded slate models increase in energy consumption from the DOE reference model. Due to the poor performance of these models, they are unsuitable substitutes for a steel-frame envelope replacement in Boulder, CO.

Table 6: Boulder, CO strip mall annual building utility performance summary

Energy End-Use	U.S. DOE Reference Model	Lightweight - C144 (< 105 lb/ft^3)		Lightweight - RBMA (< 105 lb/ft^3)		Lightweight - Ex Slate (< 105 lb/ft^3)		Normal Weight - C144 (> 125 lb/ft^3)		Normal Weight - RBMA (> 125 lb/ft^3)		Normal Weight - Ex Slate (> 125 lb/ft^3)	
	Energy (GJ)	Energy (GJ)	% Diff	Energy (GJ)	% Diff	Energy (GJ)	% Diff	Energy (GJ)	% Diff	Energy (GJ)	% Diff	Energy (GJ)	% Diff
Heating (natural gas)	817.03	931.7	-14.03%	944.76	-15.63%	939.24	-14.96%	1107.35	-35.53%	1103.27	-35.03%	1101.22	-34.78%
Cooling	47.76	43.19	9.57%	43.27	9.40%	43.11	9.74%	49.63	-3.92%	48.6	-1.76%	48.53	-1.61%
Interior Lighting	478.41	478.41	0.00%	478.41	0.00%	478.41	0.00%	478.41	0.00%	478.41	0.00%	478.41	0.00%
Exterior Lighting	180.32	180.32	0.00%	180.32	0.00%	180.32	0.00%	180.32	0.00%	180.32	0.00%	180.32	0.00%
Interior Equipment	149.43	149.43	0.00%	149.43	0.00%	149.43	0.00%	149.43	0.00%	149.43	0.00%	149.43	0.00%
Fans	144.13	149.26	-3.56%	151.61	-5.19%	150.15	-4.18%	201.03	-39.48%	200.57	-39.16%	199.91	-38.70%
Total	1817.08	1932.31	-6.34%	1947.80	-7.19%	1940.66	-6.80%	2166.17	-19.21%	2160.6	-18.91%	2157.82	-18.75%

An analysis was performed for the Boulder EnergyPlus models for an hourly heating and cooling assessment of usage over weeks that experience the highest and lowest temperatures. A separate analysis was performed for the normal weight and lightweight models to compare and contrast the results to the performance of the DOE reference model for winter and summer temperatures. These hourly energy consumptions were then combined for the entire week to report energy use.

Table 7 displays a summary of the heating energy consumption from the first of January to the eighth of January for the DOE reference model and the lightweight models. The results for the combined total of hourly heating consumption for the normal weight models are also displayed in the same table for the two critical weeks. Boulder, CO experiences cold-dry winters which requires a great amount of heating energy usage.

Table 7: Boulder, CO heating energy usage week summary

Heating:Gas Week Sum (January 1st - January 8th) - Boulder							
	Reference	LW - C144	LW - RBMA	LW - Ex Slate	NW - C144	NW - RBMA	NW - Ex Slate
Total (GJ):	67.727	77.840	79.117	78.646	93.236	93.114	92.936
Hours Operating:	183	188	189	189	192	192	192
Percent Diff:		-14.93%	-16.82%	-16.12%	-37.66%	-37.48%	-37.22%

The lightweight C144 model and lightweight recycled aggregate mortar models did not perform nearly as well as the DOE reference model in cold-dry weather conditions. Both the lightweight RBMA and lightweight expanded slate models operated for a total of 189 hours over eight days. This means that every hour, except for three over a one week period of time, the heat operated. The total heating energy consumption for the week was 79.117 GJ for the lightweight RBMA model and 78.646 GJ for the lightweight expanded slate model. Slightly lower in energy consumption, was the lightweight C144 model consuming 77.840 GJ of energy. Heat operation was only reduced by one hour for the lightweight model. The DOE reference model outperformed the lightweight models by operating the heat only 183 hours and reducing the energy consumption by approximately 10 GJ. A percent decrease of 14.93% in energy efficiency was experienced from the DOE reference model to the lightweight C144 model. An even greater percent decrease in energy efficiency was experienced for the lightweight RBMA and expanded slate models. The lightweight RBMA model decreased by 16.82% and the lightweight expanded slate model decreased by 16.12% compared to the DOE reference model. All of the models, aside from the DOE reference model appear to perform poorly in cold temperatures.

The normal weight concrete masonry models consumed an even larger amount of energy than the lightweight models. For eight days the heat operated twenty-four hours a day, 192 hours total, in contrast to the 183 hours for the DOE reference model and 188-189 hours for the lightweight models. The amount of energy consumed by heating increased approximately 25 GJ from the DOE reference model and 15 GJ from the lightweight models. 93.236 GJ were consume for the normal weight C144 model, 93.114 GJ were consumed for the normal weight RBMA model, and 92.936 GJ were consumed for the normal weight expanded slate model. The normal weight C144 model, normal weight RBMA model, and normal weight expanded slate model experienced a decrease in energy efficiency of 37.66%, 37.48%, and 37.22%. Unlike the lightweight concrete masonry models, the normal weight RBMA and expanded slate models performed better than the normal weight C144 model.

Both the lightweight models and the normal weight models performed poorly in cold temperatures compared to the DOE steel-frame reference model. Neither the lightweight nor normal weight concrete masonry constructions should be used for energy efficiency in winter Boulder, CO weather conditions. Furthermore, the normal weight recycled aggregate models performed better than the normal weight C144 model.

An hourly cooling energy consumption summary is displayed in Table 8 for the DOE reference model and the lightweight models spanning the first week of January. Over the same time period, results for the hourly cooling consumption for the normal weight models are displayed in the same table. Boulder, CO experiences relatively dry, mild summers which would require less cooling energy use.

Table 8: Boulder, CO cooling energy usage week summary

Cooling:Electricity Week Sum (July 1st - July 8th) - Boulder							
	Reference	LW - C144	LW - RBMA	LW - Ex Slate	NW - C144	NW - RBMA	NW - Ex Slate
Total (GJ):	4.248	4.130	4.160	4.144	4.786	4.725	4.718
Hours Operating:	89	93	93	93	97	98	98
Percent Diff:		2.77%	2.06%	2.45%	-12.68%	-11.24%	-11.07%

In contrast to the previous heating performance, the lightweight concrete masonry models consumed less energy for cooling than the DOE reference model. The lightweight C144 model and the lightweight recycled aggregate models require 93 hours of operation in order to cool the facility. The DOE reference model runs for four fewer hours at 89 hours over the course of the week but the whole week energy consumption is higher at 4.248 GJ. Entire week cooling energy consumptions for the lightweight models are equal to 4.130 GJ for the C144 model, 4.160 GJ for the RBMA model, and 4.144 GJ for the expanded slate model. The difference between the energy consumption of the lightweight models and the DOE reference model ranges from 0.1 GJ to 0.2 GJ. This is equal to an energy efficiency increase between the DOE reference model and the lightweight C144 model of 2.77%. The recycled aggregate mortar models performed almost as well with a 2.06% increase in efficiency for the RBMA model and a 2.45% increase in efficiency for the expanded slate model.

Unlike the lightweight concrete masonry models, the normal weight models exceed the cooling energy consumption over a one week period. The following results were obtained for the normal weight C144 model, normal weight RBMA model, and the normal weight expanded slate model respectively: 4.786 GJ, 4.725 GJ, and 4.718 GJ. These values are approximately 0.5 GJ higher in energy consumption than the DOE reference model. Not only did the normal weight concrete masonry models exceed the cooling energy consumption of the DOE reference model, the hours required to cool the facility were also increased. Cooling operated a total of 98 hours for the normal weight RBMA and expanded slate models and 97 hours for the normal weight C144 model. A decrease in energy efficiency of 12.68% was experienced for the normal weight C144 model, 11.24% for the normal weight RBMA model, and 11.07% for the normal weight expanded slate model. Both the normal weight recycled aggregate mortar models performed better than the normal weight C144 model, with the normal weight expanded slate model performing the best.

After analyzing the hourly results over the first week of July, it can be concluded that the lightweight C144 models performed very well in dry, mild weather conditions. In comparison to the DOE reference model and the lightweight concrete masonry model, the normal weight models did not perform as well. Furthermore, the normal weight recycled aggregate mortar models performed better than the normal weight C144 model.

The energy consumed to operate the fans in the strip over the first week of January and the first week of July is shown in Figure 30. These time frames are representative of the most severe weather temperatures experienced during winter and summer. Across all of the models, the fan energy consumption during the winter was greater than during the summer. The percent increase in fan energy consumption from the summer to the winter ranges from 11.01% for the DOE reference model to 14.28% for the normal weight C144 model. Overall, the normal weight models experienced the largest increase in fan energy consumption from summer to winter.

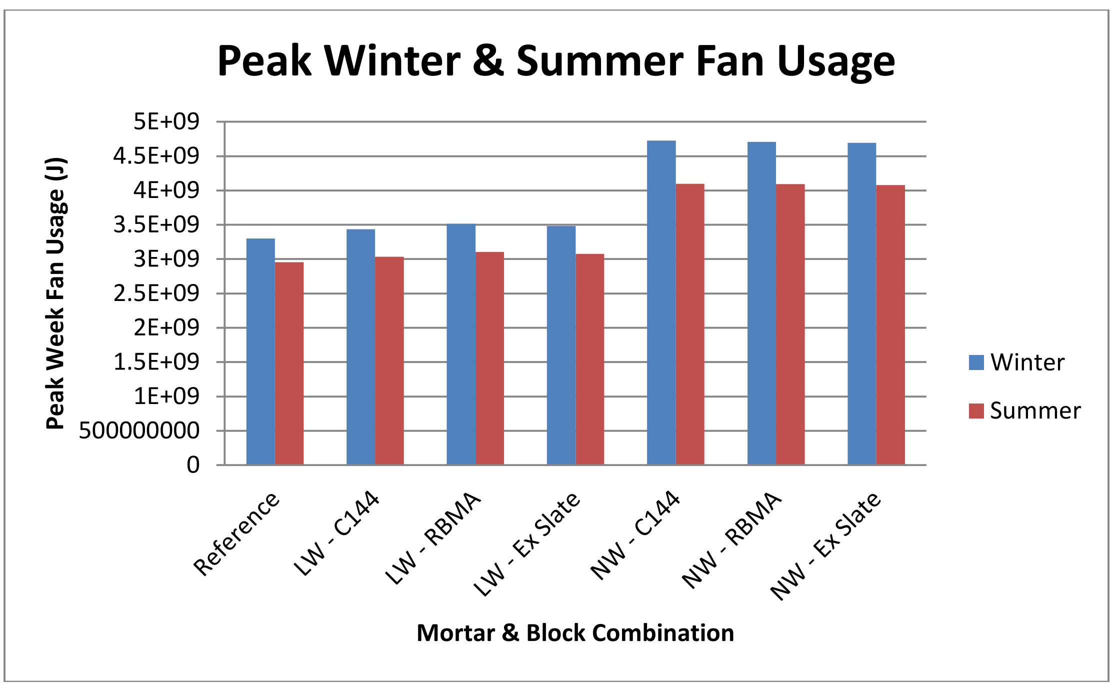

Figure 30: Boulder, CO strip mall concrete masonry model fan usage for peak summer and winter times

4.5 Los Angeles, California

4.5.1 Los Angeles, CA Reference Strip Mall Building Energy Consumption

The IECC climate zone map classifies Los Angeles, California as Zone 3B, hot-dry. The DOE describes hot-dry climate conditions as a region that has a monthly average outdoor temperature above 45°F (7°C) and receives less 20 inches (50 cm) of precipitation annually. Hot-dry climate conditions apply to both IECC zones 2 and 3.

Figures 31, 32, and 33 show the annual energy consumption by use category for the DOE reference model and the two C144 models. The largest consumption of energy for this location is lighting, ranging from 41.37% (normal weight)-42.72% (lightweight). Energy use percentages are consistent with the hot-dry climate conditions of Los Angeles. Heating, cooling, and fan energy use are significantly less than the lighting use. Heating ranges from 12.76% (DOE reference) to 14.48% (normal weight C144), cooling ranges from 3.03% (lightweight C144) to 3.81% (DOE reference), and fan usage ranges from 11.71% (lightweight C144) to 12.52% (normal weight C144). The sum of heating, cooling and fan energy consumption amounts to less than the lighting use. These values are appropriate for a hot-dry climate like Los Angeles.

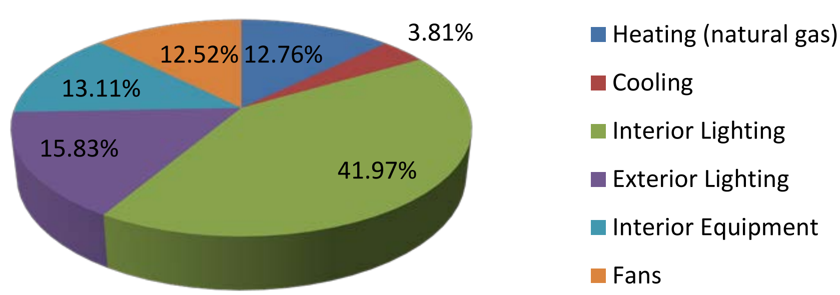

Figure 31: Los Angeles, CA strip mall DOE reference model annual energy consumption by end-use

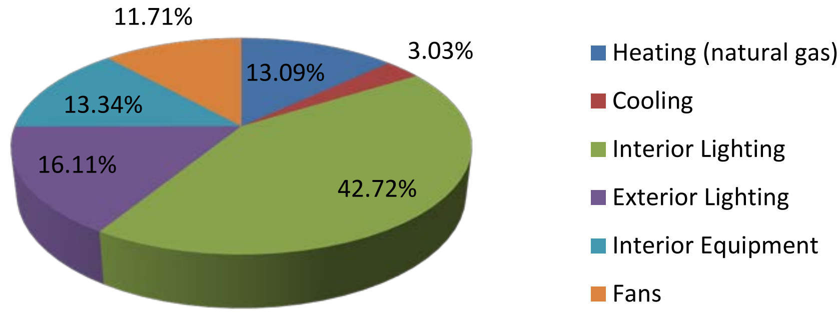

Figure 32: Los Angeles, CA strip mall lightweight C144 concrete masonry model annual energy consumption by end-use

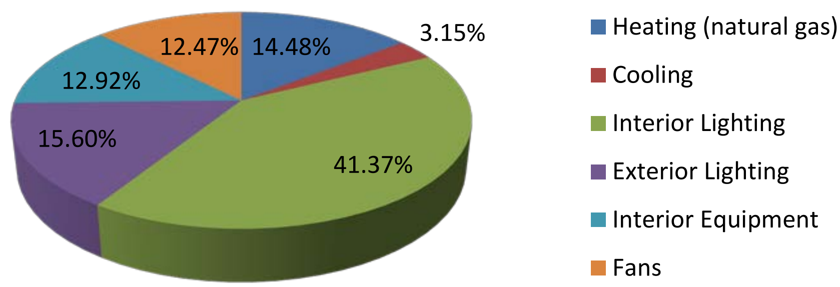

Figure 33: Los Angeles, CA strip mall normal weight C144 concrete masonry model annual energy consumption by end-use

4.5.2 Los Angeles, CA Strip Mall Building End-Use Performance with Recycled Aggregate Mortar

Annual end-use energy consumptions are displayed in Figures 34, 35, 36, and 37 for lightweight RBMA, lightweight expanded slate, normal weight RBMA, and normal weight expanded slate models. For the lightweight RBMA and lightweight expanded slate models, interior lighting is the highest consumer of end-use energy ranging from 42.69% (lightweight RBMA) to 42.73% (lightweight expanded slate). The end-use energy consumption for the lightweight C144 model interior lighting was very similar at 42.72%. Cooling consumption for both lightweight recycled aggregate mortar models was 3.00%. This only changed slightly from the C144 lightweight model at 3.03%. Heating consumption increased from the C144 lightweight model at 13.09% to the lightweight RBMA model at 13.14%. In contrast, the lightweight expanded slate model reduced the energy consumption by 0.01%. Fan energy consumption increased from 11.71% for the C144 model to 11.73% for both the RBMA and expanded slate models.

The normal weight RBMA and expanded slate models performed similar to the lightweight models. Interior lighting energy consumption increased from the normal weight C144 model at 41.37% to 41.57% (normal weight RBMA) and 41.60% (normal weight expanded slate). The amount of cooling was reduced slightly from 3.15% for the normal weight C144 model to 3.09% for the normal weight RBMA model and 3.08% for the normal weight expanded slate model. Heating end-use energy consumption was also reduced from the normal weight C144 model consumption of 14.48% to 14.42% (normal weight RBMA) and 14.39% (normal weight expanded slate). Lastly, the fan energy consumption consumed 12.26% for the normal weight RBMA model and 12.24% for the normal weight expanded slate model. The normal weight C144 model consumed 12.47% indicating a decrease in consumption of energy for fan usage for the recycled materials.

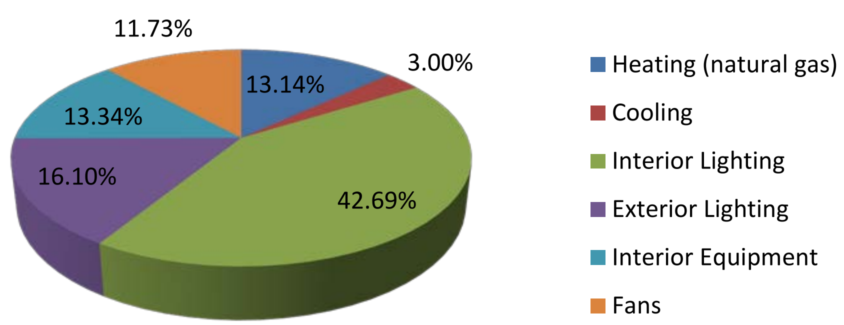

Figure 34: Los Angeles, CA strip mall lightweight concrete masonry model with RBMA mortar annual energy consumption by end-use

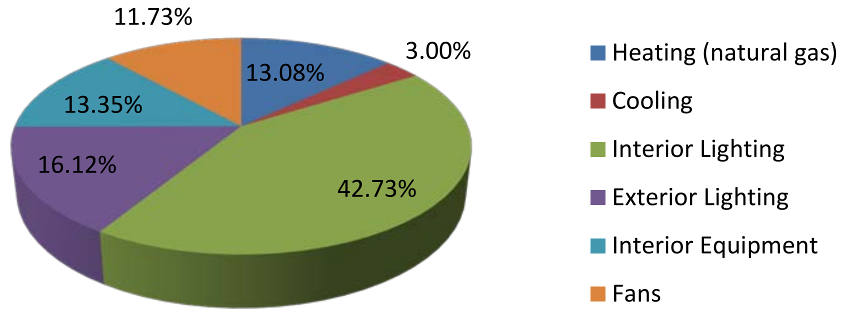

Figure 35: Los Angeles, CA strip mall lightweight concrete masonry model with expanded slate mortar annual energy consumption by end-use

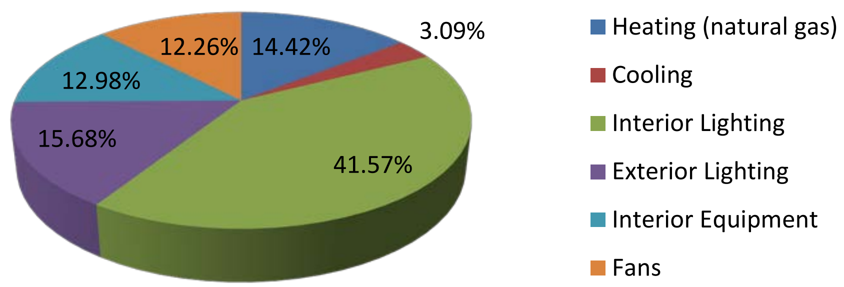

Figure 36: Los Angeles, CA strip mall normal weight concrete masonry model with RBMA mortar annual energy consumption by end-use

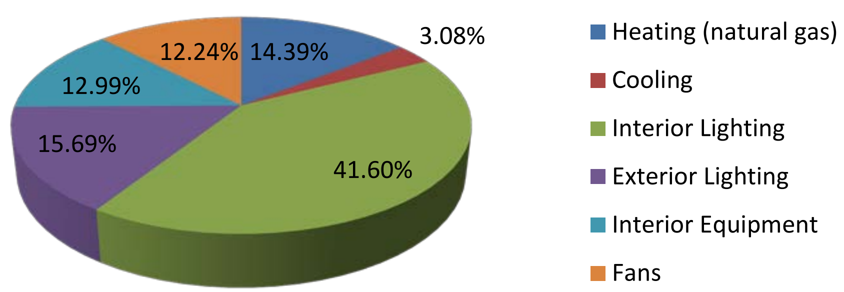

Figure 37: Los Angeles, CA strip mall normal weight concrete masonry model with expanded slate mortar annual energy consumption by end-use

Table 9 displays the percent increase and decrease of energy end-use efficiency for the DOE reference model, lightweight C144 model, lightweight recycled aggregate mortar models, normal weight C144 model, and normal weight recycled aggregate mortar models. The lightweight expanded slate model proved to be the most energy efficient for this location increasing in energy efficiency by 1.77%. Both the lightweight C144 model and lightweight RBMA model were extremely close with increased energy efficiency of 1.74% and 1.69%. The lightweight expanded slate model experienced n decrease of 0.72% for heating (natural gas), increase of 22.67% for cooling, and an increase of 7.96% for fan usage. Combined, this created a total energy increase of energy efficiency of 1.77% of the DOE reference model energy used.

Another option that would be suitable to replace the basic steel-frame construction from the three normal weight models would be the normal weight expanded slate. The normal weight expanded slate model has a decrease of 13.82% for heating (natural gas), an increase of 18.53% for cooling, and an increase of 1.35% for fan usage. This amounts to a total of 0.89% overall decrease in energy efficiency. The normal weight C144 and RBMA models have total decreases in energy efficiency of 1.46% and 0.97%.

Clearly, the lightweight expanded slate model is the more energy efficient option. However, if a normal weight option is needed the expanded slate would perform the best. Overall, all three lightweight constructions saved energy and would be an appropriate replacement for the DOE reference model steel-frame construction.

Table 9: Los Angeles, CA strip mall annual building utility performance summary

Energy End-Use	U.S. DOE Reference Model	Lightweight - C144 (< 105 lb/ft^3)		Lightweight - RBMA (< 105 lb/ft^3)		Lightweight - Ex Slate (< 105 lb/ft^3)		Normal Weight - C144 (> 125 lb/ft^3)		Normal Weight - RBMA (> 125 lb/ft^3)		Normal Weight - Ex Slate (> 125 lb/ft^3)	
	Energy (GJ)	Energy (GJ)	% Diff	Energy (GJ)	% Diff	Energy (GJ)	% Diff	Energy (GJ)	% Diff	Energy (GJ)	% Diff	Energy (GJ)	% Diff
Heating (natural gas)	145.39	146.64	-0.86%	147.24	-1.27%	146.43	-0.72%	167.48	-15.19%	165.92	-14.12%	165.49	-13.82%
Cooling	43.45	33.89	22.00%	33.64	22.58%	33.60	22.67%	36.45	16.11%	35.6	18.07%	35.4	18.53%
Interior Lighting	478.41	478.41	0.00%	478.41	0.00%	478.41	0.00%	478.41	0.00%	478.41	0.00%	478.41	0.00%
Exterior Lighting	180.45	180.45	0.00%	180.45	0.00%	180.45	0.00%	180.45	0.00%	180.45	0.00%	180.45	0.00%
Interior Equipment	149.43	149.43	0.00%	149.43	0.00%	149.43	0.00%	149.43	0.00%	149.43	0.00%	149.43	0.00%
Fans	142.69	131.12	8.11%	131.39	7.92%	131.33	7.96%	144.23	-1.08%	141.12	1.10%	140.77	1.35%
Total	1139.82	1119.94	1.74%	1120.56	1.69%	1119.65	1.77%	1156.45	-1.46%	1150.93	-0.97%	1149.95	-0.89%

An hourly analysis was performed for energy use based on heating and cooling energy consumption for peak winter and summer weeks. The weeks chosen to perform the energy consumption analyses on experience some of the lowest and highest temperatures for the year. Normal weight and lightweight models were split into separate heating and cooling data sets in order to more easily compare the performance results to the DOE reference model. The hourly data was then combined for the entire week in order to better display the data for the two critical weeks.

Displayed in Table 10 is the heating energy consumption in gigajoules, the percent difference between the DOE reference, lightweight, and normal weight models, and the number of hours the heating system operated from January 1st to January 8th. Hot-dry weather is experienced in Los Angeles, CA which requires a surprisingly large amount of heating.

Table 10: Los Angeles, CA heating energy usage week summary

Heating:Gas Week Sum (January 1st - January 8th) - Los Angeles							
	Reference	LW - C144	LW - RBMA	LW - Ex Slate	NW - C144	NW - RBMA	NW - Ex Slate
Total (GJ):	9.540	10.644	10.815	10.743	12.797	12.829	12.811
Hours Operating:	78	100	102	102	105	105	106
Percent Diff:		-11.58%	-13.36%	-12.61%	-34.14%	-34.48%	-34.29%

On average, the lightweight model and lightweight recycled aggregate mortar models consumed approximately 1 GJ more in heating energy than the DOE steel-framed reference model over the course of one week. Both the lightweight RBMA model and the lightweight expanded slate model operated for a total of 102 hours over eight days. The total energy consumption of the lightweight RBMA model and the lightweight expanded slate model are 10.815 GJ and 10.743 GJ respectively. The lightweight C144 model consumed lightly less energy than the lightweight RBMA and expanded slate models at 10.644 GJ over 100 hours. Out of the four models analyzed for heating consumption over the peak winter week, the DOE reference model consumed less energy than the lightweight models for heating at 9.540 GJ over 78 hours. The difference in energy efficiency varies for all three lightweight models. A decrease in energy efficiency of 11.58% was experienced from the DOE reference model to the lightweight C144 model. The recycled aggregate mortar models performed worse with a decrease in efficiency of 13.36% for the lightweight RBMA model and 12.61% for the lightweight expanded slate model. All three lightweight models appear to perform poorly in cold weather.

The normal weight concrete masonry models consumed approximately 3 GJ more than the DOE reference model over a one week period for heating. These models also consumed approximately 2 GJ more in energy than the lightweight models. The total amount of energy consumed through heating amounted to 12.797 GJ for the normal weight C144 model, 12.829 GJ for the normal weight RBMA model, and 12.811 GJ for the normal weight expanded slate model. The heat operated for a total of 105 hours for the normal weight C144 and normal weight RBMA models over eight days. During the same time frame, the normal weight expanded slate model heat operated for 106 hours. Heating operation hours are significantly greater than the DOE reference model which only operates for 78 hours. A total decrease of 34.14% in energy efficiency from the DOE reference model to the normal weight C144 model was experienced. The normal weight RBMA and expanded slate models were close in energy efficiency with a decrease of 34.48% and 34.29%.

The lightweight and normal weight models were both less energy efficient than the DOE steel-frame reference model. Also, the recycled aggregate mortar models performed poorer than their respective concrete masonry C144 models. Over the eight days, the concrete masonry models' heat operated between 22 to 28 more hours than the DOE reference model. Neither the lightweight nor normal weight models would be suitable energy efficient substitutes for cooler weather conditions.

From July 1st to July 8th data was collected every hour for cooling energy consumption and summed in order to compare and contrast the results. Results for the lightweight models, normal weight models, and DOE reference model combined week cooling consumptions are displayed in Table 11. Cooling usage was relatively low due to the dry summer weather Los Angeles experiences.

Table 11: Los Angeles, CA cooling energy usage week summary

Cooling:Electricity Week Sum (July 1st - July 8th) - Los Angeles							
	Reference	LW - C144	LW - RBMA	LW - Ex Slate	NW - C144	NW - RBMA	NW - Ex Slate
Total (GJ):	1.012	0.704	0.689	0.689	0.706	0.683	0.677
Hours Operating:	72	67	66	67	68	68	66
Percent Diff:		30.43%	31.93%	31.90%	30.21%	32.51%	33.04%

While comparing and contrasting the DOE reference model and the lightweight concrete masonry models, it was observed that the lightweight models are significantly lower in cooling energy consumption. The DOE reference model requires a total of 72 hours of cooling and 1.012 GJ of energy consumption for the first week of July. During the same time period, the lightweight C144 model required 67 hours and 0.704 GJ, the lightweight RBMA model required 66 hours and 0.689 GJ, and the lightweight expanded slate model required 67 hours and 0.689 GJ. All of the lightweight concrete masonry models cooling systems operated for fewer hours and consumed less energy cooling the facility during some of the warmest temperatures throughout the year. The percent increase between the DOE reference model and the lightweight C144 model, RBMA model, and expanded slate model are 30.43%, 31.93%, and 31.90%. Of the three lightweight concrete masonry models, the RBMA model had the highest increase in energy efficiency. Both the lightweight recycled aggregate mortar models proved to be more energy efficient than the lightweight C144 model.

Like the lightweight concrete masonry models, the normal weight concrete masonry models performed better during Los Angeles summer temperatures than the DOE reference model. The cooling energy consumption and hours required for cooling were very similar to the results for the lightweight models. The normal weight C144 model consumed 0.706 GJ, the normal weight RBMA model consumed 0.683 GJ, and the normal weight expanded slate model consumed 0.677 GJ compared to the DOE reference model. The number of hours required to cool the facility were less than the DOE reference model for the normal weight models. The normal weight C144 model and normal weight RBMA model operated 68 hours and the normal weight expanded slate model operated 66 hours. Overall, an increase of 30.21%, 32.51%, and 33.04% energy efficiency was experienced from the normal weight C144 model, the normal weight RBMA model, and the normal weight expanded slate model respectively. The normal weight expanded slate model had the largest increase in energy efficiency when compared to the DOE reference model and the normal weight C144 model. Both of the normal weight recycled aggregate mortar variations performed better than the normal weight C144 model.

While comparing and contrasting the lightweight concrete masonry models, the normal weight concrete masonry models, and the DOE reference model, it was observed that the lightweight and normal weight models are more energy efficient. Not only did the lightweight and normal weight concrete masonry C144 models perform better than the DOE reference model, but the recycled aggregate mortar models performed even better. Both types of models performed well in the Los Angeles summer weather conditions.

Following the energy analyses performed on the heating and cooling energy consumption was an analysis on fan energy consumption. Data from the energy consumption from January 1st to January 8th and June 1st to June 8th is displayed in Figure 38. Each of these weeks represents peak temperatures experienced in Los Angeles during winter and summer. The percent difference between the summer and winter fan energy consumption was calculated. 3.60% increase in energy consumption is experienced from summer to winter for all of the models. During each season the fans consistently operated the same amount for every model.

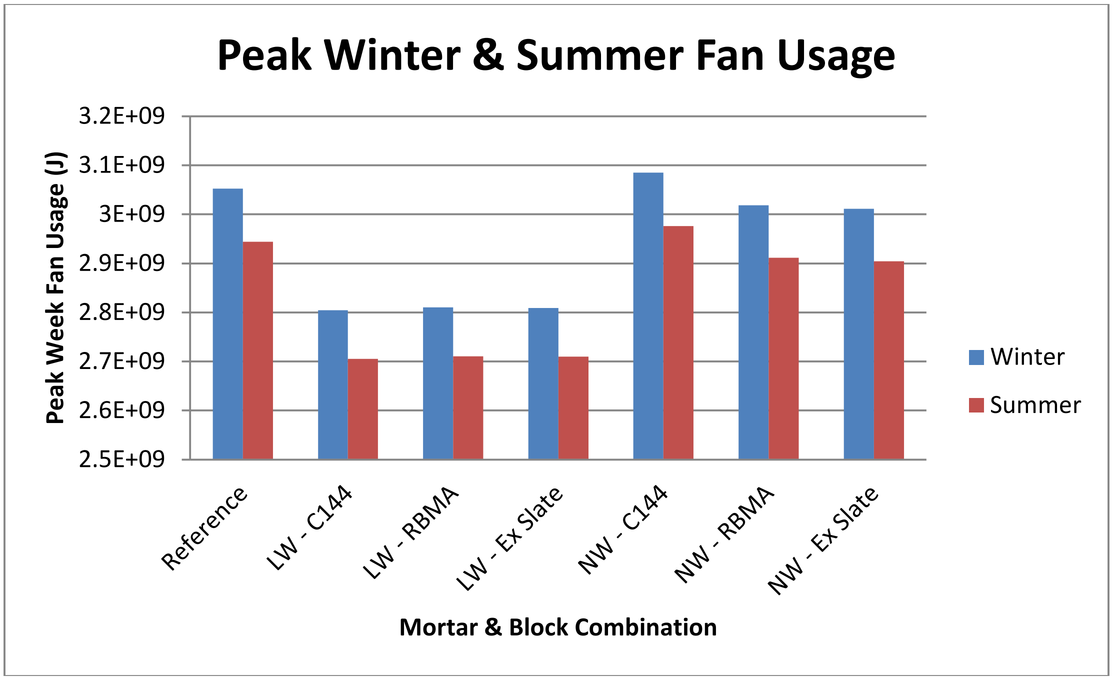

Figure 38: Los Angeles, CA strip mall concrete masonry model fan usage for peak summer and winter times

4.6 Minneapolis, Minnesota

4.6.1 Minneapolis, MN Reference Strip Mall Building Energy Consumption

The IECC classifies Minneapolis, Minnesota as Zone 6A, cold-humid. Cold-humid is described by the DOE the same as cold-dry: a region that has between 5,400 and 9,000 heating degree days (65°F). The letter “A” is what indicates the humidity level as moist, otherwise known as humid.

Figures 39, 40, and 41 show the annual energy consumption by end-use for the DOE reference model and the two C144 models. Although lighting is a large consumer of the end-use energy percentage, it shies in comparison to the percentage of energy consumed by heating. The amount of heat consumed ranges from 58.47% (DOE reference) to 63.72% (normal weight C144) and is appropriate for the cold-humid building location climate.

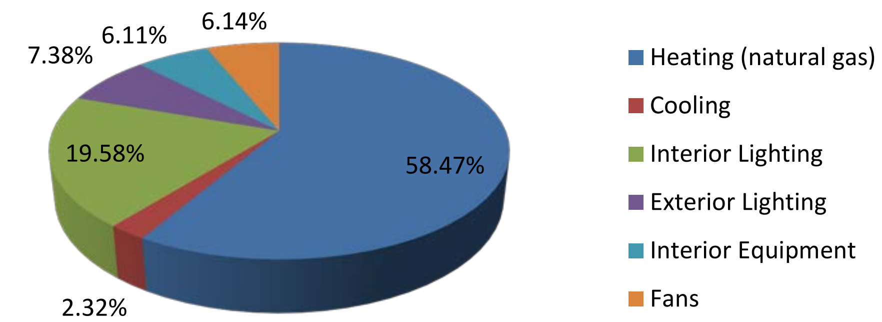

Figure 39: Minneapolis, MN strip mall DOE reference model annual energy consumption by end-use

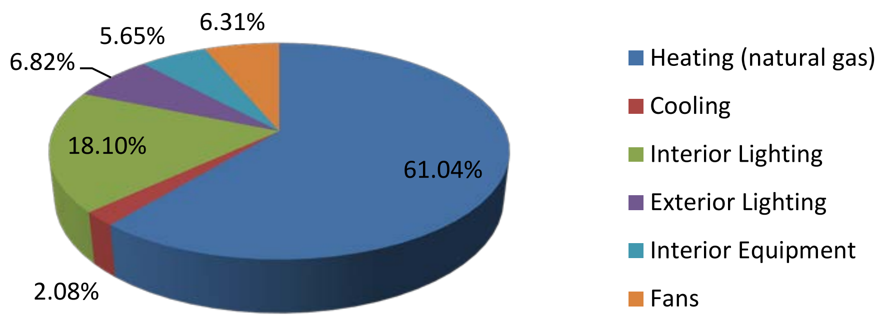

Figure 40: Minneapolis, MN strip mall lightweight C144 concrete masonry model annual energy consumption by end-use

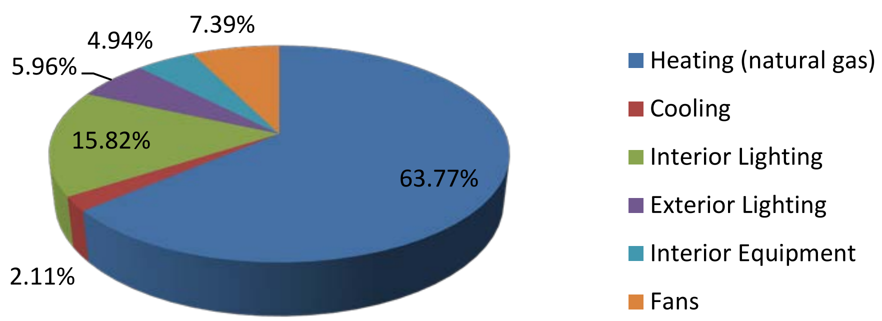

Figure 41: Minneapolis, MN strip mall normal weight C144 concrete masonry model annual energy consumption by end-use

4.6.2 Minneapolis, MN Strip Mall Building End-Use Performance with Recycled Aggregate Mortar

Shown in Figures 42, 43, 44, and 45 are lightweight RBMA, lightweight expanded slate, normal weight RBMA, and normal weight expanded slate mortar models. Due to the cold temperatures experienced in Minneapolis, the majority of the end-use energy consumption for both the lightweight and normal weight recycled aggregate mortar models is through heating.

The lightweight models results vary slightly from the normal weight results. Heating consumption experienced an increase in usage from the lightweight C144 model at 61.04% to the lightweight RBMA model at 61.28% and the lightweight expanded slate model at 61.19%. The second largest consumer of energy for the lightweight models remained the interior lighting. Interior lighting decreased from the lightweight C144 model to the lightweight recycled aggregate models. The lightweight C144 model interior lighting consumed 18.10% of the energy whereas, the RBMA model interior lighting consumed 17.90% and the expanded slate model interior lighting consumed 17.98%. Cooling was used very little for the lightweight C144 and recycled aggregate mortar models due to the more severe winters experienced in Minnesota. The C144 model only used 2.08% and both the RBMA and expanded slate models decreased by 0.01%, consuming a total of 2.07% of the end-use energy for cooling. Fan energy consumption experienced similar results as heating energy consumption. There was an increase from the lightweight C144 model (6.31%) to the lightweight RBMA (6.40%) and the lightweight expanded slate model (6.37%).

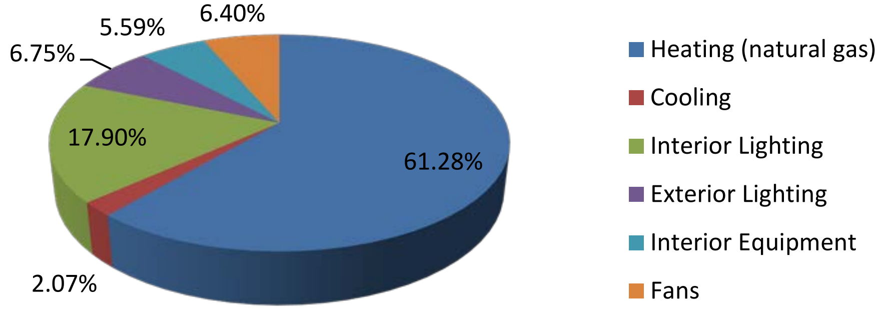

Figure 42: Minneapolis, MN strip mall lightweight concrete masonry model with RBMA mortar annual energy consumption by end-use

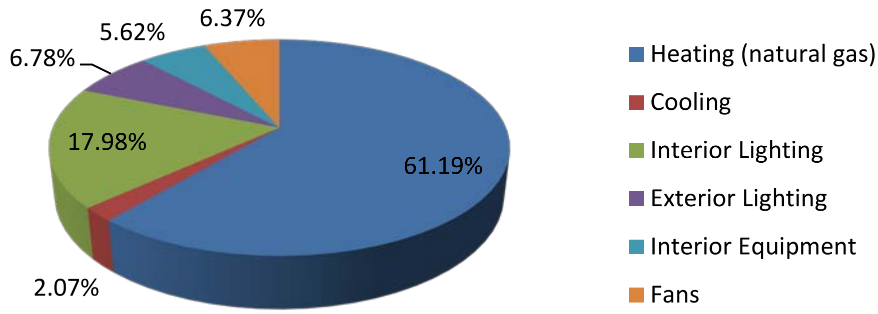

Figure 43: Minneapolis, MN strip mall lightweight concrete masonry model with expanded slate mortar annual energy consumption by end-use

In contrast to the lightweight models, the normal weight heating consumption decreased from the normal weight C144 model to the recycled aggregate mortar models. These values ranged from 63.77% (normal weight C144) to 63.73% (normal weight RBMA). Another contrast between the lightweight and normal weight models is the decrease in interior lighting usage between the normal weight C144 model and the recycled aggregate mortar models. The normal weight model values increase from the C144 model at 15.82%, the RBMA model at 15.84%, and the expanded slate model at 15.87%. Although a slight change occurred in the cooling energy consumption, the consumption decreased from the normal weight C144 model to the normal weight recycled aggregate models. The normal weight C144 model consumed 2.11% while the normal weight RBMA and expanded slate models consumed 2.09%. Unlike heating and interior lighting, both the lightweight and normal weight recycled aggregate mortar models decreased in cooling energy consumption. Lastly, the fan energy consumption remained the same at 7.39% from the normal weight C144 model to the normal weight RBMA model. The expanded slate fan energy consumption was lower by 0.01% at a total of 7.38%.

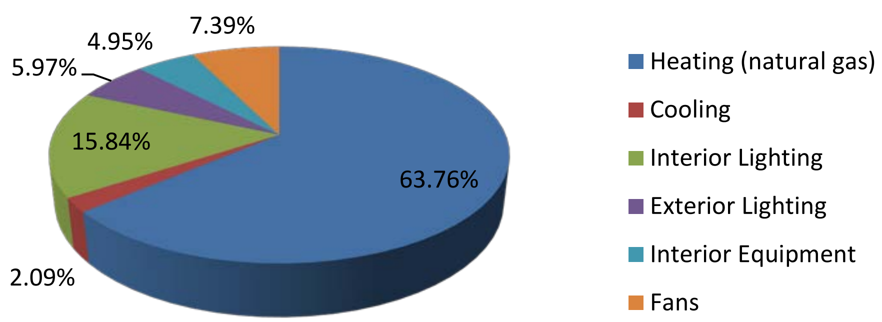

Figure 44: Minneapolis, MN strip mall normal weight concrete masonry model with RBMA mortar annual energy consumption by end-use

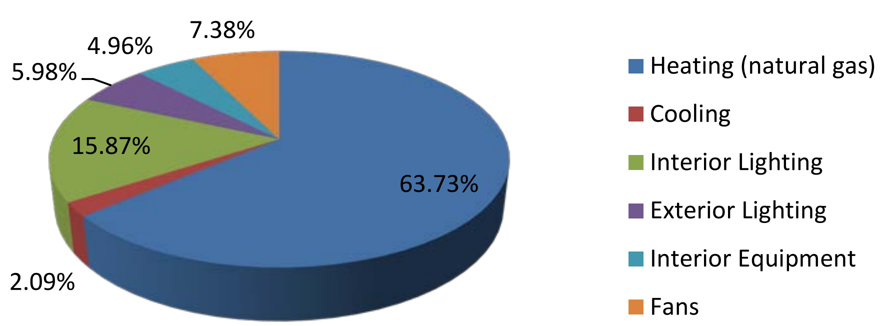

Figure 45: Minneapolis, MN strip mall normal weight concrete masonry model with expanded slate mortar annual energy consumption by end-use

Table 12 shows the percent increase and decrease in the annual building utility performance summary between the DOE reference model, lightweight C144 model, lightweight recycled aggregate mortar models, normal weight C144 model, and the normal weight recycled aggregate mortar models. The best option from the models would be the lightweight C144 model due to the minimal deviation from the C144 model energy usage. Heating efficiency decreased by 12.91%, cooling efficiency increased by 2.89%, and the fan efficiency decreased by 11.15% for the lightweight C144 model. Both the lightweight RBMA and lightweight expanded slate decreased the overall energy efficiency by 9.35% and 8.89%.

In contrast, the normal weight models deviated a significant amount from the DOE reference model data. Energy efficiency was decreased for the normal weight C144 model by 23.77%, the normal weight RBMA model by 23.60%, and the normal weight expanded slate by 23.39%. Out of the three normal weight models, the expanded slate model would be the best option. Energy efficiency decreased by 34.49% for heating (natural gas), 11.18% for cooling, and 48.35% for fan usage.

Both the lightweight model and the normal weight expanded slate models would be poor substitutions for the DOE steel-frame construction due to their energy inefficiency. If a concrete masonry system was mandated, the lightweight masonry would be the most energy efficient option.

Table 12: Minneapolis, MN strip mall annual building utility performance summary

Energy End-Use	U.S. DOE Reference Model	Lightweight - C144 (< 105 lb/ft^3)		Lightweight - RBMA (< 105 lb/ft^3)		Lightweight - Ex Slate (< 105 lb/ft^3)		Normal Weight - C144 (> 125 lb/ft^3)		Normal Weight - RBMA (> 125 lb/ft^3)		Normal Weight - Ex Slate (> 125 lb/ft^3)	
	Energy (GJ)	Energy (GJ)	% Diff	Energy (GJ)	% Diff	Energy (GJ)	% Diff	Energy (GJ)	% Diff	Energy (GJ)	% Diff	Energy (GJ)	% Diff
Heating (natural gas)	1428.9	1613.34	-12.91%	1637.43	-14.59%	1628.09	-13.94%	1928.84	-34.99%	1925.82	-34.78%	1921.67	-34.49%
Cooling	56.70	55.06	2.89%	55.44	2.22%	55.20	2.65%	63.95	-12.79%	63.27	-11.59%	63.04	-11.18%
Interior Lighting	478.41	478.41	0.00%	478.41	0.00%	478.41	0.00%	478.41	0.00%	478.41	0.00%	478.41	0.00%
Exterior Lighting	180.31	180.31	0.00%	180.31	0.00%	180.31	0.00%	180.31	0.00%	180.31	0.00%	180.31	0.00%
Interior Equipment	149.43	149.43	0.00%	149.43	0.00%	149.43	0.00%	149.43	0.00%	149.43	0.00%	149.43	0.00%
Fans	149.95	166.67	-11.15%	171.05	-14.07%	169.44	-13.00%	223.65	-49.15%	223.22	-48.86%	222.45	-48.35%
Total	2443.7	2643.22	-8.16%	2672.07	-9.35%	2660.88	-8.89%	3024.59	-23.77%	3020.46	-23.60%	3015.31	-23.39%

The next EnergyPlus model data analysis performed was a summary of hourly heating and cooling consumption over peak temperature weeks for winter and summer. Comparisons of the models were analyzed by separating them into lightweight model results and normal weight model results then comparing them to the DOE reference model results for winter and summer. The data was then summed for the week for overall weekly usage.

Values for heating consumption per hour sum for the first week of January, the first through the eighth, are displayed in Table 13 for the lightweight concrete masonry models. The same information is also displayed in Table 13 for the normal weight concrete masonry models. Minneapolis, MN has extremely cold winters which resulted in very high hourly heat energy consumption.

Table 13: Minneapolis, MN heating energy usage week summary

Heating:Gas Week Sum (January 1st - January 8th) - Minneapolis							
	Reference	LW - C144	LW - RBMA	LW - Ex Slate	NW - C144	NW - RBMA	NW - Ex Slate
Total (GJ):	112.235	127.709	129.825	129.061	153.742	153.633	153.306
Hours Operating:	191	192	192	192	192	192	192
Percent Diff:		-13.79%	-15.67%	-14.99%	-36.98%	-36.89%	-36.59%

The number of hours the heat was operating was consistent for the lightweight C144 model, the lightweight recycled aggregate mortar models, and the DOE reference model. The heat operated for twenty-four hours a day for eight days for the lightweight models and only turned off for one hour for the C144 model. Even though the models ran the same number of hours, the DOE reference model consumed 112.235 GJ which is significantly less than any of the lightweight models. The lightweight C144, lightweight

RBMA, and lightweight expanded slate consumed 127.709 GJ, 129.825 GJ, and 129.061 GJ. Of the three lightweight masonry models, the lightweight C144 model consumed the least amount of energy for heating. The DOE reference model performs very well in peak winter temperatures compared to the lightweight C144 model and the lightweight recycled aggregate mortar models. A decrease in energy efficiency was experienced from the DOE reference model to the lightweight models. 13.79%, 15.67%, and 14.99% decrease in energy efficiency was experienced for the lightweight C144, RBMA, and expanded slate models respectively. The lightweight recycled aggregate mortar models performed more poorly than the lightweight C144 model.

The normal weight concrete masonry performed differently than the lightweight concrete masonry models. The heat still operated twenty-four hours a day for the entire week but the overall energy consumption for the normal weight model was approximately 41 GJ more than the DOE reference model. 153.742 GJ were consumed for the normal weight C144, 153.633 GJ were consumed for the normal weight RBMA model, and 153.306 GJ were consumed for the expanded slate model. All of these values have an extremely large deviation from the DOE reference model. The increase in energy consumption translates as a decrease in energy efficiency. A decrease in energy efficiency of 36.98%, 36.89%, and 36.59% was experienced for the normal weight C144, RBMA, and expanded slate models. Although there was an overall decrease in energy efficiency, the normal weight recycled aggregate mortar models performed slightly better than the normal weight C144 model. Of the two recycled aggregate variations, the expanded slate model performed the best.

Based on the analyses between the lightweight, normal weight, and DOE reference models, all of the lightweight and normal weight models performed very poorly. However, the normal weight recycled aggregate models performed better than the normal weight C144 model. The DOE steel-frame reference model is best suited for high heating consumption and very cold temperatures in Minneapolis, MN.

Data was collected every hour for cooling energy consumption from July 1st to July 8th, one of the warmest weeks of the year. Table 14 displays the hourly cooling energy consumption summed for the week for the lightweight and DOE reference models. The same information for the normal weight models is displayed in the same table. Minneapolis, Minnesota experiences warm, dry summer weather which greatly affects the amount of cooling energy used.

Table 14: Minneapolis, MN cooling energy usage week summary

Cooling:Electricity Week Sum (July 1st - July 8th) - Minneapolis							
	Reference	LW - C144	LW - RBMA	LW - Ex Slate	NW - C144	NW - RBMA	NW - Ex Slate
Total (GJ):	3.662	3.578	3.603	3.586	4.173	4.132	4.115
Hours Operating:	77	80	82	81	89	89	88
Percent Diff:		2.29%	1.61%	2.06%	-13.96%	-12.84%	-12.38%

The DOE reference model and the lightweight models are very similar in the amount of energy consumed in order to cool the strip mall. The lightweight C144 model consumes 3.578 GJ, the lightweight RBMA model consumes 3.603 GJ, and the lightweight expanded slate model consumes 3.586 GJ. The DOE reference model consumes more energy than all three lightweight models at 3.662 GJ over the first week of July. Although the DOE reference model consumes more energy, it requires only 77 hours to cool the facility versus 80 for the C144 model, 82 for the RBMA model, and 81 for the expanded slate model. There was an increase in the energy efficiency of the lightweight concrete masonry models from the DOE reference models. The lightweight C144 model increased 2.29% in energy efficiency with the lightweight RBMA and expanded slate models slightly less at 1.61% and 2.06%.

Unlike the lightweight concrete masonry models, the normal weight concrete masonry models consume more energy than the DOE reference model throughout the first week of July. For the entire week the normal weight C144 model consumed 4.173 GJ over 89 hours, the normal weight RBMA model consumed 4.132 GJ over 89 hours, and the expanded slate model consumed 4.115 GJ over 88 hours. The DOE reference model consumed 0.5 GJ less for the week and only operated the cooling system for 77 hours. From the DOE reference model to the normal weight C144 model there was a significant decrease in energy efficiency. The normal weight C144 model experienced a decrease of 13.96%. The normal weight recycled aggregate mortar variations did not perform as poorly as the normal weight C144 model but were very close. The expanded slate model performed the best with a decrease of 12.38% and the RBMA model experienced a decrease of 12.84%.

Through analyzing the week cooling energy usage totals and the hours required to cool the strip mall, it can be concluded that the lightweight concrete masonry models would be a suitable energy efficient substitute for the DOE steel-frame reference model. Out of the three normal weight models analyzed the expanded slate model performed the best. The normal weight concrete masonry models are only slightly higher in energy consumption but would not be the best choice available.

Next, the energy consumed to operate the fans in the strip mall was analyzed. Figure 46 displays the energy consumed by the fans over the first weeks of January and July. The first weeks of January and July represent peak temperatures of the year. The graph shows that fan energy consumption was higher during the winter than the summer. The percent difference from summer to winter ranges from 16.83% for the DOE reference model to 20.34% for the normal weight C144 model. From the graph it can be seen that the normal weight models consumed more energy during both seasons than the DOE reference model and the lightweight models.

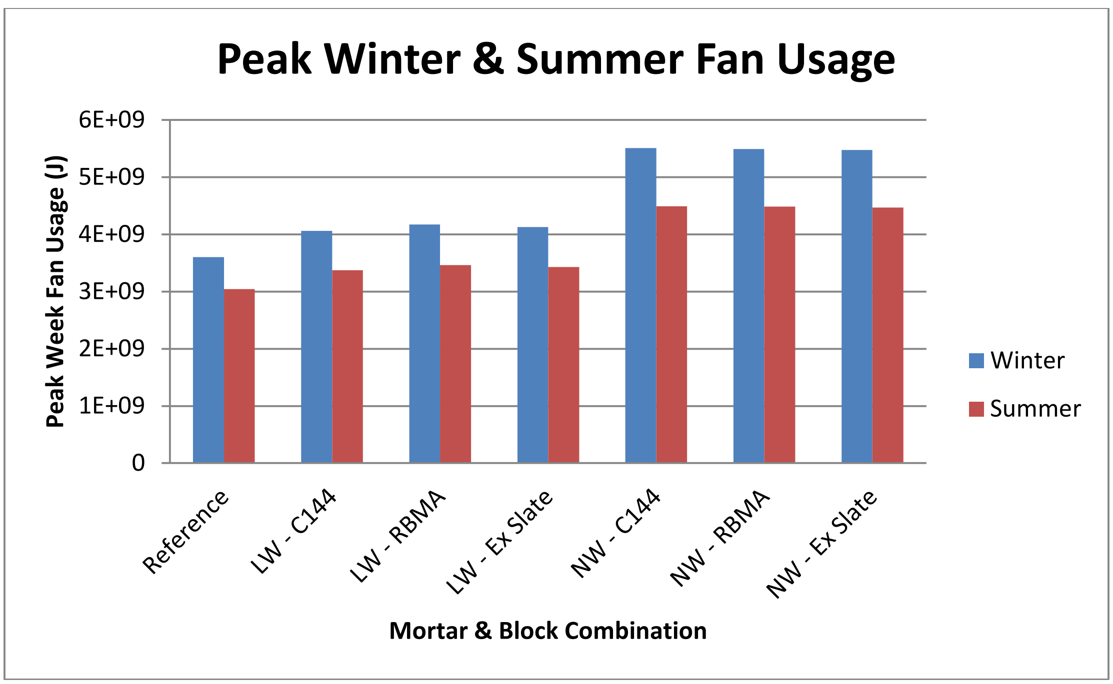

Figure 46: Minneapolis, MN strip mall concrete masonry model fan usage for peak summer and winter times

4.7 Baltimore, Maryland

4.7.1 Baltimore, MD Reference Strip Mall Building Energy Consumption

Baltimore, Maryland is classified as Zone 4A, mixed-humid, according to the IECC climate map. The DOE defines mixed-humid as “a region that receives more than 20 inches (50 cm) of annual precipitation, has approximately 5,400 heating degree days (65°F basis) or fewer, and where the average monthly outdoor temperature drops below 45°F (7°C) during the winter months,” (U.S. DOE, 2011). This description applies to both IECC zones 3 and 4 in category A.

Figures 47, 48, and 49 show the annual energy consumption by end-use for the three models generated in Baltimore, Maryland. For this simulation, the largest consumer of end-use energy was heating ranging from 42.36% (DOE reference) - 49.30% (normal weight C144). The least consumer of end-use energy was cooling ranging from 4.79% (normal weight C144)-5.45% (DOE reference). The vast difference in heating and cooling consumption is reasonable due to Baltimore having very cold winters and moderate summers.

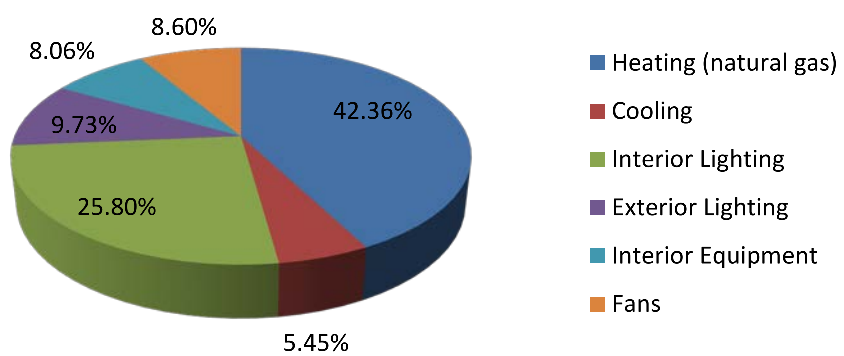

Figure 47: Baltimore, MD strip mall DOE reference model annual energy consumption by end-use

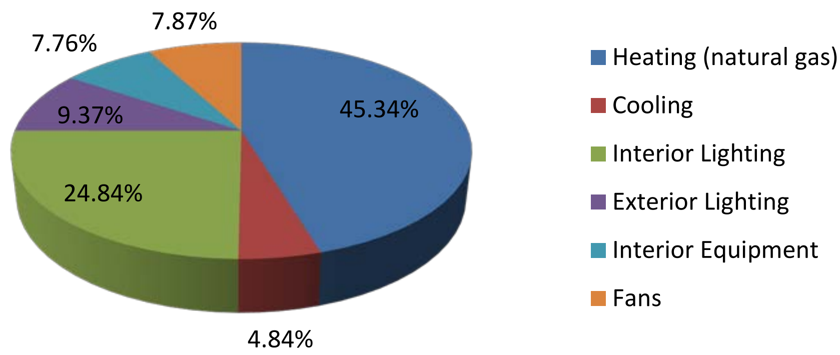

Figure 48: Baltimore, MD strip mall lightweight C144 concrete masonry model annual energy consumption by end-use

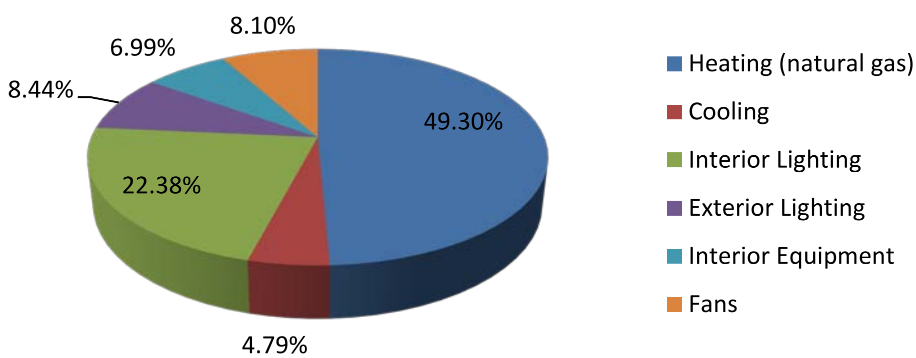

Figure 49: Baltimore, MD strip mall normal weight C144 concrete masonry model annual energy consumption by end-use

4.7.2 Baltimore, MD Strip Mall Building End-Use Performance with Recycled Aggregate Mortar

Figures 50, 51, 52, and 53 show the annual end-use energy consumption for lightweight RBMA, lightweight expanded slate, normal weight RBMA, and normal weight expanded slate mortar models. The largest consumer of energy for the lightweight and normal weight recycled aggregate mortar models is the heating. This corresponds with the high heating energy consumption for the C144 models and the cool climactic conditions in Baltimore.

Heating remains the main consumer of energy for the lightweight C144, RBMA, and expanded slate models. There is an increase in heating energy consumption from the lowest, the C144 model at 45.34%, to the highest; the RBMA model at 45.65%. The energy consumption for the expanded slate lies between these two percentages at 45.55%. The second largest consumer of energy for the lightweight models is the interior lighting. Interior lighting energy consumption decreases between the lightweight C144 model and the lightweight recycled aggregate mortar models. The lightweight C144 model consumes 24.84% whereas the lightweight RBMA model consumes 24.67% and the expanded slate model consumes 24.72%. Cooling consumes the least amount of energy out of the six energy consumptions investigated. The energy consumption for cooling decreases from 4.84% for the lightweight C144 model to 4.82% for the lightweight RBMA and expanded slate models. Lastly, the fan energy consumption only varies by 0.01% between the lightweight C144 and expanded slate models at 7.87% and the lightweight RBMA model at 7.86%.

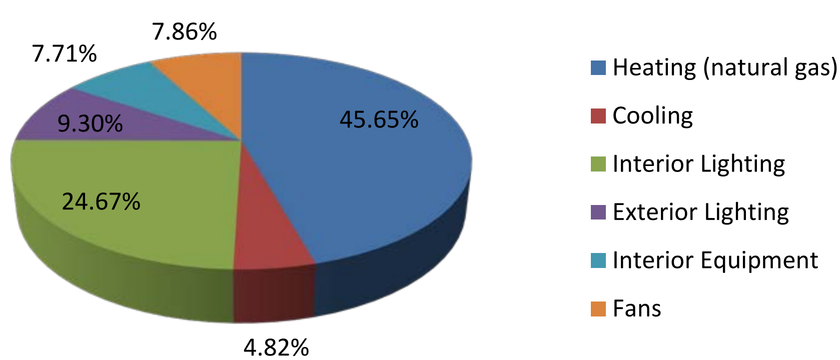

Figure 50: Baltimore, MD strip mall lightweight concrete masonry model with RBMA mortar annual energy consumption by end-use

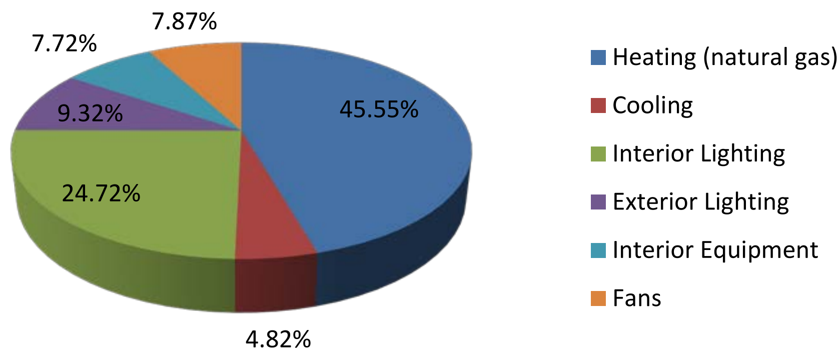

Figure 51: Baltimore, MD strip mall lightweight concrete masonry model with expanded slate mortar annual energy consumption by end-use

There are a few similarities between trends for the lightweight and normal weight models. The first trend is the increase in heating energy consumption. The normal weight C144 model consumes 48.30% of the overall energy usage with the normal weight expanded slate model at 49.32% and the normal weight RBMA model at 49.37%. Both the lightweight and the normal weight RBMA models exceed the other two models in the respective categories. In contrast to the lightweight models, the normal weight recycled aggregate models increase in interior lighting usage from the normal weight C144 model. The normal weight C144 model energy consumption is equal to 22.38% while the normal weight RBMA and expanded slate interior lighting consumption are equal to 22.43% and 22.46% respectively. Like the lightweight models for Baltimore, the cooling energy consumption decreases from 4.79% for the normal weight C144 model to 4.74% for both the normal weight RBMA and expanded slate models. The final piece of data, fan energy consumption, does not correspond to any lightweight model patterns. Fan energy consumption decreases from 8.10% for the normal weight C144 model to 8.00% for the normal weight RBMA model and 7.99% for the normal weight expanded slate model.

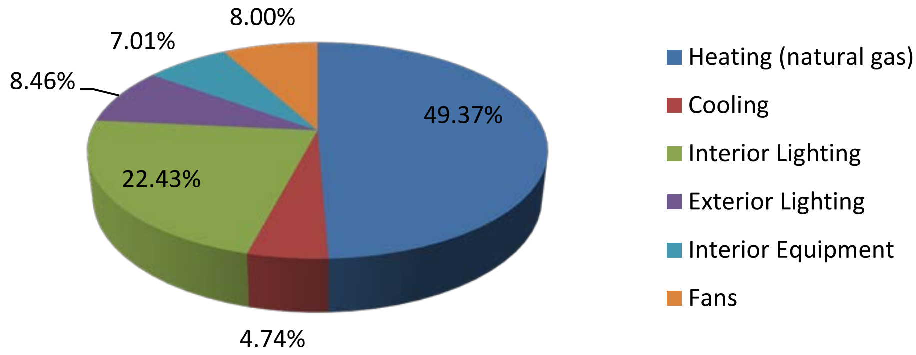

Figure 52: Baltimore, MD strip mall normal weight concrete masonry model with RBMA mortar annual energy consumption by end-use

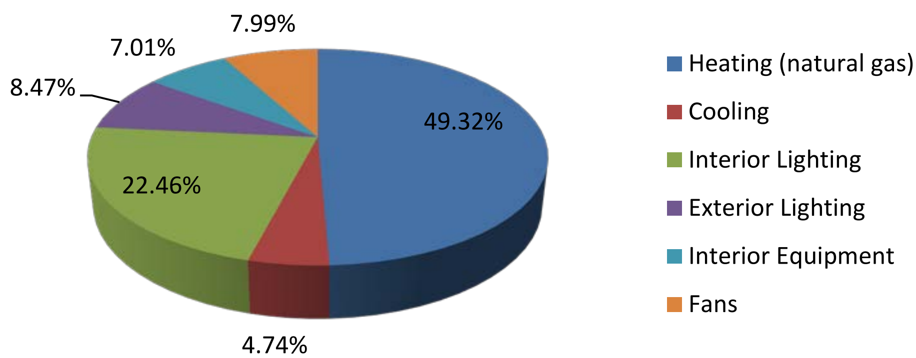

Figure 53: Baltimore, MD strip mall normal weight concrete masonry model with expanded slate mortar annual energy consumption by end-use

Table 15 shows the percent change in annual building utility performance summary between the DOE reference model, the lightweight C144 model, the lightweight recycled aggregate mortar models, the normal weight C144 model, and the normal weight recycled aggregate mortar models. The lightweight C144 model increased in energy use but was significantly less than the other model results. Heating decreased in energy efficiency by 11.20%, cooling increased in energy efficiency by 7.74%, and fan usage increased in energy efficiency by 5.02% for a net decrease of 3.89% for the lightweight C144 model. The lightweight recycled aggregate mortar models also decreased in energy efficiency. The lightweight RBMA model decreased by 4.59% and the lightweight expanded slate model decreased by 4.37%.

Like the lightweight models, the normal weight models decreased in energy efficiency across all three models; however, the decrease was much greater. The normal weight C144 model and the normal weight RBMA model are 15.28% and 15.04% less energy efficiency than the DOE steel-frame envelope model. The lowest energy consumer for the normal weight models is the expanded slate. Energy efficiency for the expanded slate model decreased by 14.90% from the DOE reference model. Heating (natural gas) decreased the most by 33.80%, with a 6.74% decrease in fan consumption, and a negligible decrease of 0.02% for cooling.

Even though six types of concrete masonry building envelopes were simulated, the DOE reference model is still more energy efficient. The use of recycled materials would not outweigh the cost of the increased energy consumption over time.

Table 15: Baltimore, MD strip mall annual building utility performance summary

Energy End-Use	U.S. DOE Reference Model	Lightweight - C144 (< 105 lb/ft^3)		Lightweight - RBMA (< 105 lb/ft^3)		Lightweight - Ex Slate (< 105 lb/ft^3)		Normal Weight - C144 (> 125 lb/ft^3)		Normal Weight - RBMA (> 125 lb/ft^3)		Normal Weight - Ex Slate (> 125 lb/ft^3)	
	Energy (GJ)	Energy (GJ)	% Diff	Energy (GJ)	% Diff	Energy (GJ)	% Diff	Energy (GJ)	% Diff	Energy (GJ)	% Diff	Energy (GJ)	% Diff
Heating (natural gas)	785.36	873.29	-11.20%	885.35	-12.73%	881.52	-12.24%	1053.77	-34.18%	1053.07	-34.09%	1050.8	-33.80%
Cooling	101.05	93.23	7.74%	93.42	7.55%	93.28	7.69%	102.39	-1.33%	101.17	-0.12%	101.07	-0.02%
Interior Lighting	478.41	478.41	0.00%	478.41	0.00%	478.41	0.00%	478.41	0.00%	478.41	0.00%	478.41	0.00%
Exterior Lighting	180.4	180.4	0.00%	180.40	0.00%	180.40	0.00%	180.4	0.00%	180.4	0.00%	180.4	0.00%
Interior Equipment	149.43	149.43	0.00%	149.43	0.00%	149.43	0.00%	149.43	0.00%	149.43	0.00%	149.43	0.00%
Fans	159.54	151.53	5.02%	152.37	4.49%	152.22	4.59%	173.14	-8.52%	170.56	-6.91%	170.29	-6.74%
Total	1854.19	1926.29	-3.89%	1939.38	-4.59%	1935.26	-4.37%	2137.54	-15.28%	2133.04	-15.04%	2130.4	-14.90%

An analysis was performed for the Baltimore EnergyPlus models for an hourly assessment of heating and cooling usage over weeks that experience the highest and lowest temperatures. Normal weight model results and lightweight model results were separated into two tables in order to compare and contrast the DOE reference model results for winter and summer as a summary for the entire week.

A summary of the hourly heating usage data collected from January 1st to January 8th for the DOE reference model and the lightweight models is displayed in Table 16. Table 16 also displays the results for the summary of the hourly heating consumption for the normal weight models over the same time period. Baltimore has a mixed-humid climate which can experience both warm and cold temperatures while being humid.

Table 16: Baltimore, MD heating energy usage week summary

Heating:Gas Week Sum (January 1st - January 8th) - Baltimore							
	Reference	LW - C144	LW - RBMA	LW - Ex Slate	NW - C144	NW - RBMA	NW - Ex Slate
Total (GJ):	36.387	41.304	41.961	41.791	50.355	50.421	50.304
Hours Operating:	143	143	143	143	168	168	168
Percent Diff:		-13.51%	-15.32%	-14.85%	-38.39%	-38.57%	-38.24%

Mixed-humid weather conditions were not ideal for the performance of the lightweight model and the lightweight recycled aggregate mortar models. The DOE reference model consumed 36.387 GJ for heating while operating 143 hours over eight days. Like the DOE reference model, heating in the lightweight models also operated 143 hours over eight days. In contrast, the lightweight models consumed approximately 5 GJ more than the DOE reference model in order to heat the facility. The total heating energy consumption for the week was 41.304 GJ for the lightweight C144 mode, 41.961 GJ for the lightweight RBMA model, and 41.791 GJ for the lightweight expanded slate model. From the DOE reference model to the lightweight C144 model a 13.51% decrease in energy efficiency was experienced. The lightweight recycled aggregate mortar variations were even less energy efficient with the RBMA decreasing 15.32% and the expanded slate decreasing 14.85%. Like many of the other locations, the DOE reference model outperformed the lightweight models and proved more energy efficiency.

The table shows that each of the normal weight concrete masonry models consumed approximately 14 GJ more than the DOE reference model over a one week period for heating. Also, approximately 9 GJ more was consumed in heating energy usage than the lightweight models. The total amount of energy consumed through heating amounted to 50.355 GJ for the normal weight C144 model, 50.421 GJ for the normal weight RBMA model, and 50.304 GJ for the normal weight expanded slate model. All of the normal weight models operated the facility heat for 168 hours over eight days. During the same period of time the DOE reference model and the lightweight models only required the use of heat 143 hours. From the DOE reference model to the normal weight C144 model, the energy efficiency decreased 38.39%. The normal weight RBMA performed worse than the normal weight C144 model with energy efficiency decreasing 38.57%. In contrast, the normal weight expanded slate model performed better. The energy efficiency only decreased 38.24%.

The DOE steel-frame model was more energy efficient in cold weather than the lightweight models and normal weight models. Overall the heat operated for the same amount of hours per week as the lightweight models but the lightweight models still consumed more energy. The normal weight models required more hours of heat operating but also consumed a significantly higher amount of energy. The normal weight expanded slate model did outperform the normal weight C144 model. Both the lightweight models and the normal weight models would not be energy efficient substitutes.

Energy consumption was recorded hourly from July 1st to July 8th in order to investigate how each building envelope reacted to peak summer temperatures. Table 17 displays these hourly values summarized for the lightweight concrete masonry models and the DOE reference model. Table 17 displays the same information for the normal weight concrete masonry models and the DOE reference model.

Table 17: Baltimore, MD cooling energy usage week summary

Cooling:Electricity Week Sum (July 1st - July 8th) - Baltimore							
	Reference	LW - C144	LW - RBMA	LW - Ex Slate	NW - C144	NW - RBMA	NW - Ex Slate
Total (GJ):	6.459	6.154	6.180	6.172	6.762	6.711	6.704
Hours Operating:	99	101	101	101	105	105	105
Percent Diff:		4.73%	4.32%	4.43%	-4.69%	-3.90%	-3.80%

The lightweight models were consistently lower in cooling energy consumption than the DOE reference model. During peak cooling hours, which were typically midday, the hourly energy consumption was lower for the lightweight models than the DOE reference model. The number of hours required to cool the lightweight models were consistently 101 hours however, the energy consumption varied marginally. The lightweight cooling energy consumed for each model was 6.154 GJ for the C144 model, 6.180 GJ for the RBMA model, and 6.172 GJ for the expanded slate model. The DOE reference model was slightly higher at 6.459 GJ over 99 hours. The lightweight concrete masonry models consumed less energy over more hours than the DOE reference model.

The lightweight C144 model experienced an energy efficiency increase of 4.73% from the DOE reference model. Both the lightweight RBMA and expanded slate models also increased in energy efficiency at 4.32% and 4.43% respectively.

In contrast to the lightweight concrete masonry models, the normal weight concrete masonry models consumed more energy cooling the facility than the DOE reference model. At the highest summer temperatures during the day, the normal weight C144 models consumed more energy. Although they consumed more energy, it was only approximately 0.25 GJ over the course of one week for each model. Over 105 hour total for the week, the normal weight concrete masonry models consumed 6.762 GJ for the C144 model, 6.711 GJ for the RBMA model, and 6.704 GJ for the expanded slate model. The DOE reference model required less hours over the week to cool the strip mall than the normal weight models at 99 hours. A decrease in energy efficiency was seen from the DOE reference model to the normal weight C144 model at 4.69%. The normal weight RBMA and expanded slate models also decreased in energy efficiency however, it was less than the normal weight C144 model. The expanded slate model decreased in energy efficiency by 3.80% and the RBMA decreased in energy efficiency by 3.90%. The normal weight expanded slate model performed better than the normal weight C144 model and the normal weight RBMA model.

After comparing and contrasting the lightweight and normal weight concrete masonry models to the DOE steel-frame reference model, it was observed that the lightweight models performed better than the DOE reference model. Although the normal weight models consumed more energy for cooling than the DOE reference model, the difference in energy consumption is not large. The normal weight expanded slate model performed better than other two normal weight concrete masonry models. Overall, the lightweight concrete masonry models would be a suitable substitute for the DOE reference model.

Next, an analysis on the amount of energy required to operate the fans over the first week of January and July was performed. Figure 54 compares the energy consumptions for all seven models for both winter and summer peak temperatures. For all of the models, the fan energy consumption during the winter was much higher than the summer. The percent increase from summer to winter ranges from 3.97% for the lightweight C144 model to 5.16% for the normal weight C144 model. Overall, the normal weight concrete masonry models consumed a larger amount of energy than any of the other models during the peak temperature weeks.

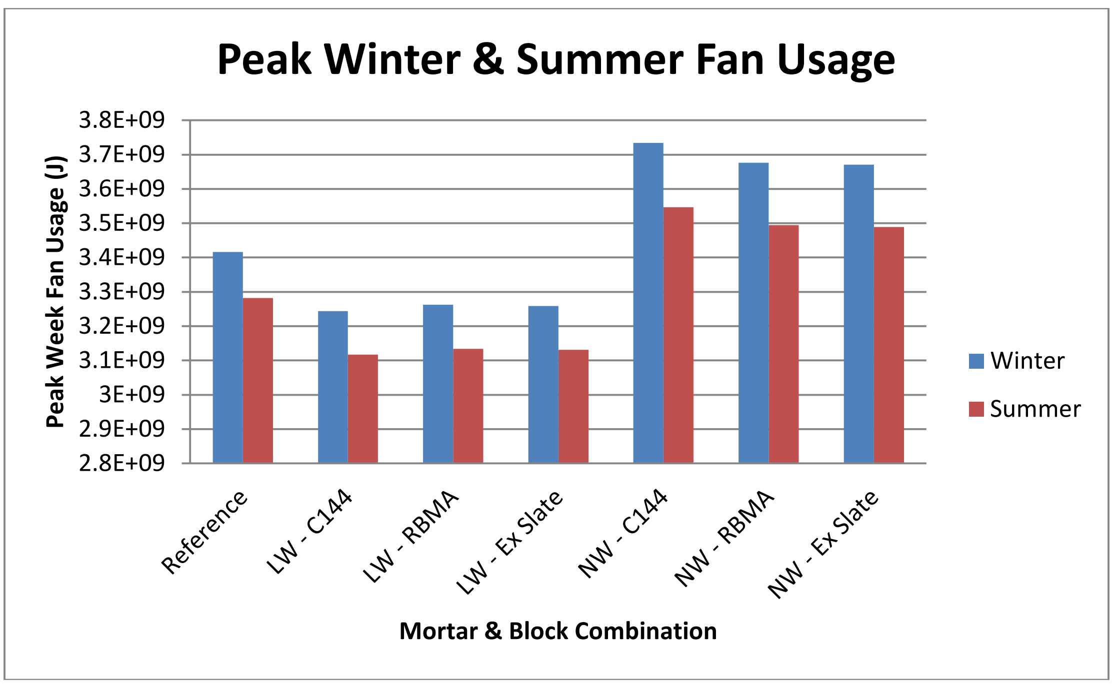

Figure 54: Baltimore, MD strip mall concrete masonry model fan usage for peak summer and winter times

4.8 Phoenix, Arizona

4.8.1 Phoenix, AZ Reference Strip Mall Building Energy Consumption

Phoenix, Arizona is classified by the IECC climate map as Zone 2B, hot-dry. Mix-humid climate conditions are defined as a region where the monthly outdoor temperature remains greater than 45°F (7°C) year round and less than 20 inches (50 cm) of precipitation is received annually (U.S. DOE 2011). These conditions are applicable to IECC zones 2 and 3.

Figures 55, 56, and 57 shows the percentages of annual energy consumption by end-use for the DOE reference, lightweight concrete masonry, and normal weight concrete masonry simulations in Phoenix. Ranging from 31.88% (normal weight)-33.97% (lightweight) energy consumption, lighting consumes the most energy. Cooling consumes the second most amount of energy ranging from 18.46% (lightweight)-20.09% (normal weight). A hot-dry climate requires more cooling than other climate classifications.

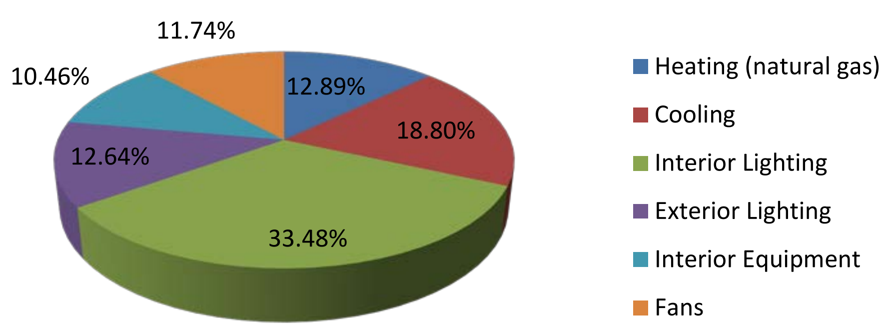

Figure 55: Phoenix, AZ strip mall DOE reference model annual energy consumption by end-use

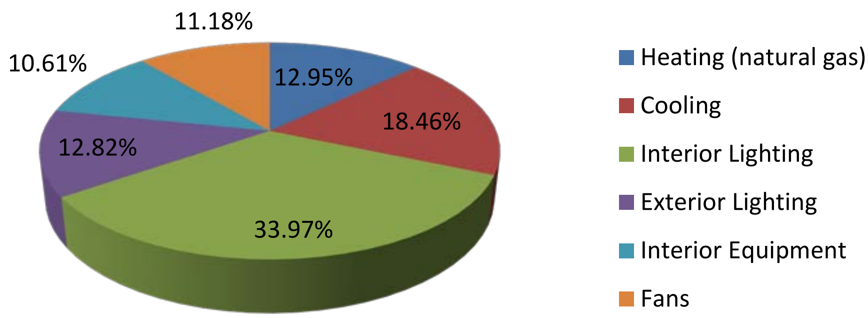

Figure 56: Phoenix, AZ strip mall lightweight C144 concrete masonry model annual energy consumption by end-use

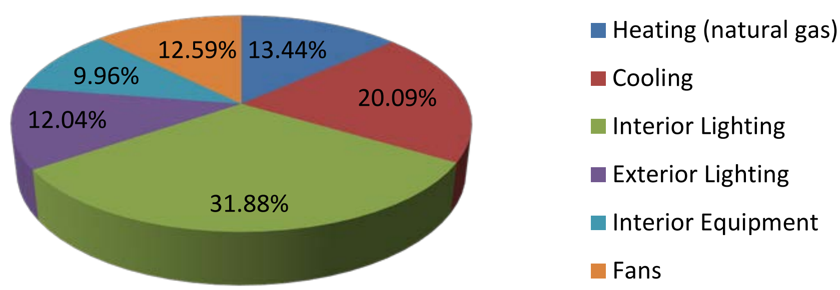

Figure 57: Phoenix, AZ strip mall normal weight C144 concrete masonry model annual energy consumption by end-use

4.8.2 Phoenix, AZ Strip Mall Building End-Use Performance with Recycled Aggregate Mortar

Lightweight RBMA, lightweight expanded slate, normal weight RBMA, and normal weight expanded slate mortar models annual end-use energy consumption is displayed in Figures 58, 59, 60, and 61. For the lightweight and normal weight models, the main consumers of energy are interior lighting and cooling. More energy is required for cooling due to the warmer climactic conditions in Phoenix.

Interior lighting for the lightweight models consumes nearly a third of the overall annual energy consumption. The lightweight C144 model consumes 33.97% while the lightweight RBMA and lightweight expanded slate models consume 33.87% and 33.93% respectively. The second largest consumer of the annual end-use energy is the cooling. Cooling increases from the lightweight C144 model to the lightweight recycled aggregate mortar models. The lightweight C144 model cooling consumption is equal to 18.46% and increases to 18.58% for the lightweight RBMA model and 18.54% for the expanded slate model. Like the cooling energy consumption, the fan energy consumption also increases from the lightweight C144 model to the lightweight recycled aggregate mortar models. 11.18% of the energy is consumed by fans for the lightweight C144 model, 11.26% is consumed for the lightweight RBMA model, and 11.23% is consumed for the lightweight expanded slate model. Heating is the last main consumer of annual end-use energy for the lightweight models. Energy consumption for heating decreases from the lightweight C144 model to the lightweight recycled aggregate mortar models. The lightweight C144 model energy consumption is equal to 12.95% and the recycled aggregate mortar models consume 12.93% (RBMA) and 12.90% (expanded slate).

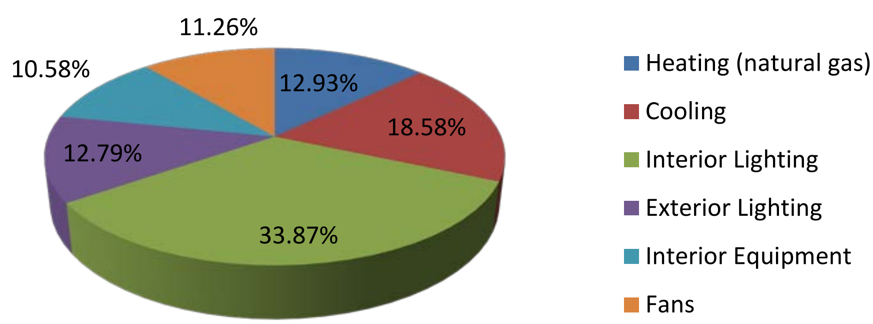

Figure 58: Phoenix, AZ strip mall lightweight concrete masonry model with RBMA mortar annual energy consumption by end-use

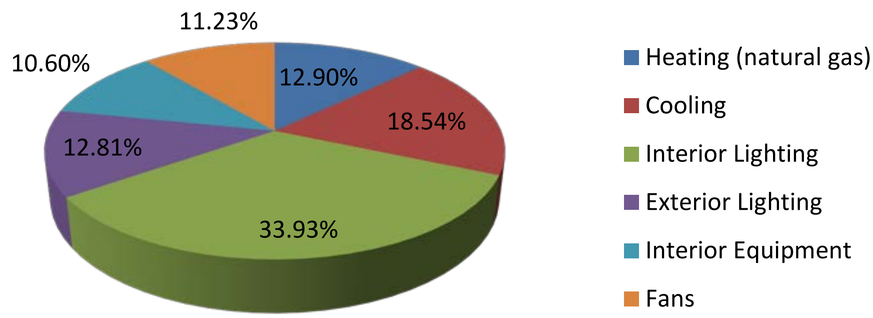

Figure 59: Phoenix, AZ strip mall lightweight concrete masonry model with expanded slate mortar annual energy consumption by end-use

The Phoenix normal weight models are similar to the lightweight models in that the interior lighting also consumes approximately one-third of the annual end-use energy consumption. In contrast the interior lighting consumption for the normal weight models decreases from the C144 model to the recycled aggregate mortar models. The normal weight C144, RBMA, and expanded slate models are equal to 31.88%, 32.04%, and 32.08% respectively. The second largest consumer of end-use energy is cooling. Similar to the lightweight models, the normal weight model cooling consumption decreases from the normal weight C144 model to the recycled aggregate mortar models. 20.09% is consumed by the normal weight C144 model, 20.04% is consumed by the normal weight RBMA model, and 20.01% is consumed by the normal weight expanded slate model. Unlike the lightweight models, the next largest consumer of energy for the normal weight models is heating. The energy consumption increases from 13.44% for the normal weight C144 model to 13.38% (RBMA) and 13.37% (expanded slate). The final main consumer of energy for the normal weight Phoenix models is the fan usage. The fan usage percentage decreases from 12.59% for the C144 model to 12.44% for RBMA and 12.41% for expanded slate.

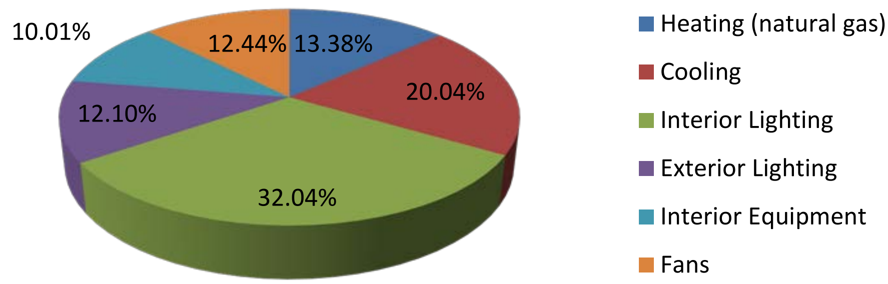

Figure 60: Phoenix, AZ strip mall normal weight concrete masonry model with RBMA mortar annual energy consumption by end-use

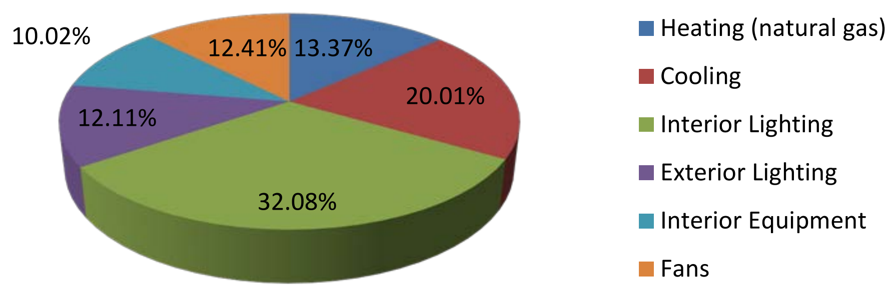

Figure 61: Phoenix, AZ strip mall normal weight concrete masonry model with expanded slate mortar annual energy consumption by end-use

In Table 18, percent increases and decreases in energy end-use are shown for the Phoenix strip mall DOE reference model, lightweight C144 model, lightweight recycled aggregate mortar models, normal weight C144 model, and normal weight recycled aggregate mortar models. The lightweight concrete masonry model increased in energy end-use efficiency for heating, cooling, and fan usage. Heating increased by 0.94%, cooling increased by 3.23%, and fan usage increased by 6.14% for a total increase in energy end-use efficiency of 1.45%. Both the lightweight RBMA model and the lightweight expanded slate model also increased energy consumption efficiency by

1.15% and 1.33% respectively. Any of these options would be an energy efficient replacement in Phoenix for the DOE steel-frame reference model.

Unlike the lightweight models, the normal weight models increased in energy consumption for all three models. Out of the three normal weight models the expanded slate performed the best with an energy consumption efficiency decrease of 4.36%. The normal weight expanded slate model decreased in energy consumption efficiency for heating, cooling, and fan usage. Heating (natural gas) decreased by 8.28%, cooling decreased by 11.05%, and fan energy usage decreased by 10.33% for a total decrease in energy end-use efficiency of 4.36%. The normal weight C144 model decreased by 4.99% and the normal weight RBMA model decreased by 4.49% in energy efficiency therefore making the normal weight expanded slate model the best option out of the three models.

According to the data the lightweight concrete masonry building envelope responds to high heat climate conditions better than the normal weight concrete masonry and steel-frame reference models. Due to the reduction in energy consumption any of the lightweight concrete masonry options would be ideal.

Table 18: Phoenix, AZ strip mall annual building utility performance summary

Energy End-Use	U.S. DOE Reference Model	Lightweight - C144 (< 105 lb/ft^3)		Lightweight - RBMA (< 105 lb/ft^3)		Lightweight - Ex Slate (< 105 lb/ft^3)		Normal Weight - C144 (> 125 lb/ft^3)		Normal Weight - RBMA (> 125 lb/ft^3)		Normal Weight - Ex Slate (> 125 lb/ft^3)	
	Energy (GJ)	Energy (GJ)	% Diff	Energy (GJ)	% Diff	Energy (GJ)	% Diff	Energy (GJ)	% Diff	Energy (GJ)	% Diff	Energy (GJ)	% Diff
Heating (natural gas)	184.17	182.44	0.94%	182.61	0.85%	181.90	1.23%	201.67	-9.50%	199.82	-8.50%	199.42	-8.28%
Cooling	268.71	260.04	3.23%	262.51	2.31%	261.42	2.71%	301.44	-12.18%	299.26	-11.37%	298.4	-11.05%
Interior Lighting	478.41	478.41	0.00%	478.41	0.00%	478.41	0.00%	478.41	0.00%	478.41	0.00%	478.41	0.00%
Exterior Lighting	180.62	180.62	0.00%	180.62	0.00%	180.62	0.00%	180.62	0.00%	180.62	0.00%	180.62	0.00%
Interior Equipment	149.43	149.43	0.00%	149.43	0.00%	149.43	0.00%	149.43	0.00%	149.43	0.00%	149.43	0.00%
Fans	167.80	157.49	6.14%	159.06	5.21%	158.33	5.64%	188.89	-12.57%	185.77	-10.71%	185.13	-10.33%
Total	1429.14	1408.43	1.45%	1412.64	1.15%	1410.11	1.33%	1500.46	-4.99%	1493.31	-4.49%	1491.41	-4.36%

Hourly heating and cooling energy consumption over peak temperature weeks for winter and summer were analyzed for the EnergyPlus model results. Results of the models were analyzed by separating them into lightweight model results and normal weight model results then comparing them to the DOE reference model results for winter and summer. After analyzing them they were summed into one table for the entire week.

Table 19 shows the heating consumption per hour from January 1st to January 8th for the lightweight concrete masonry models. The normal weight concrete masonry models are also shown in Table 19. Phoenix, Arizona is considered to have a mixed-humid climate which resulted in moderate usage of the heating and cooling systems.

Table 19: Phoenix, AZ heating energy usage week summary

Heating:Gas Week Sum (January 1st - January 8th) - Phoenix							
	Reference	LW - C144	LW - RBMA	LW - Ex Slate	NW - C144	NW - RBMA	NW - Ex Slate
Total (GJ):	12.934	13.832	13.943	13.885	15.399	15.383	15.369
Hours Operating:	75	95	97	97	94	97	98
Percent Diff:		-6.95%	-7.80%	-7.35%	-19.06%	-18.94%	-18.83%

The heating energy consumption difference between the lightweight model and lightweight recycled aggregate mortar models, and the DOE reference model is no greater than 1.10 GJ. Both the lightweight RBMA model and the lightweight expanded slate model operated for a total of 97 hours over eight days. The lightweight C144 model number of heating operating hours only slightly deviated from the other two models with 95 hours. The DOE reference model only consumes a total of 12.934 GJ over 75 hours for the entire peak week in January whereas the lightweight C144, RBMA, and expanded slate models consume a total of 12.832 GJ, 13943 GJ, and 13.885 GJ respectively. Only a slight decrease in energy efficiency occurred. The lightweight C144 model, RBMA model, and expanded slate model experienced a 6.95%, 7.80%, and 7.35% decrease in energy efficiency. The lightweight C144 model performed the best with the lightweight expanded slate performing next best. The moderate heating energy usage is due to the less extreme winter temperatures experienced in Phoenix.

The normal weight C144 model and normal weight recycled aggregate mortar models experienced a similar amount of hours for heating operation. Hours of heating operation for the normal weight models are 94 (C144), 97 (RBMA), and 98 (expanded slate). Even though the normal weight C144 model operates heat the fewest number of hours for the normal weight models, it consumed the largest amount of energy at 15.399 GJ. Energy consumption for the remaining two models are 15.383 GJ for the normal weight RBMA model and 15.369 for the normal weight expanded slate model. The normal weight models deviate from the C144 model approximately 2.4 GJ. Unlike the lightweight models, the normal weight models experienced a large decrease in energy efficiency. The normal weight C144 model decreased 19.06%, the normal weight RBMA model decreased 18.94%, and the normal weight expanded slate model decreased 18.83%. Of the three normal weight models, the expanded slate model performed the best.

Overall, the lightweight concrete masonry models did not stray far from each other for the amount of heating energy consumed. This trend is also true for the normal weight concrete masonry models however, the normal weight expanded slate model performed better than the other normal weight models. The DOE reference model remains the best option for a more energy efficient building due to the increased energy consumption for heating during the peak winter temperatures in Phoenix.

From July 1st to July 8th cooling consumption data was recorded every hour. Table 20 displays a summary of the hourly values for the lightweight concrete masonry models and the DOE reference model. The same information is displayed in Table 20 but for the normal weight concrete masonry models and the DOE reference model. The cooling system ran for a moderate amount of the day due to the mixed-humid climate and hot summer weather.

Table 20: Phoenix, AZ cooling energy usage week summary

Cooling:Electricity Week Sum (July 1st - July 8th) - Phoenix							
	Reference	LW - C144	LW - RBMA	LW - Ex Slate	NW - C144	NW - RBMA	NW - Ex Slate
Total (GJ):	11.004	11.024	11.152	11.104	12.785	12.727	12.694
Hours Operating:	105	109	109	109	112	111	111
Percent Diff:		-0.18%	-1.34%	-0.91%	-16.19%	-15.66%	-15.36%

The lightweight concrete masonry models consumed more energy over the first week of July than the DOE reference model. Even though the DOE reference model consumed more energy during peak hours, the weekly total energy consumption was 11.004 GJ which is less than all of the lightweight models. Cooling energy consumption for the lightweight models were 11.024 GJ for the C144 model, 11.152 GJ for the RBMA model, and 11.104 GJ for the expanded slate model. All of the lightweight models required 109 hours to cool the facility which is 4 hours more per week than the DOE reference model. The increase in cooling energy consumption for the lightweight models correlates with the increase in the amount of hours required to cool the facility. There was a slight decreased in energy efficiency for the lightweight models. The C144 model decreased 0.18%, the RBMA model decreased 1.34%, and the expanded slate model decreased 0.91%. Overall, the lightweight C144 model performed the best.

Like the lightweight concrete masonry models, the normal weight models consumed more energy cooling the strip mall in Phoenix than the DOE reference model. The normal weight models consumed 12.785 GJ over 112 hours for the C144 model, 12.727 GJ over 111 hours for the RBMA model, 12.694 GJ over 111 hours for the expanded slate model. The DOE reference model only consumed 11.004 GJ over 105 hours. The normal weight models were considerable less energy efficient than the lightweight models. The normal weight expanded slate model performed the best with a decreased energy efficiency of 15.36% from the DOE reference model. The normal weight C144 and RBMA models decreased in energy efficiency by 16.19% and 15.66%.

The lightweight and normal weight models both consume more energy than the DOE reference model while cooling the strip mall. Out of the six alternative building envelope constructions, the lightweight models were the closest in cooling energy consumption to the DOE reference model. Although the normal weight models were much higher in energy consumption, the normal weight expanded slate model outperformed the other normal weight models. In conclusion, the DOE reference model outperformed the lightweight and normal weight models and was also the most energy efficient option.

Figure 62 shows fan energy consumption for the first week of January and the first week of July. The first weeks of January and July represent the peak temperature weeks for winter and summer. During the winter and summer, the winter time period used more energy to operate the fans than the summer time period however, the fan energy consumption during the winter was only a small amount more than the summer. When calculating the percent difference between the summer and winter energy consumption for each model it was found that each model had a 3.60% increase from summer to winter. Overall, the lightweight concrete masonry models consumed the least amount of energy and the normal weight concrete masonry models consumed the most but the increase in energy consumption between seasons was consistent.

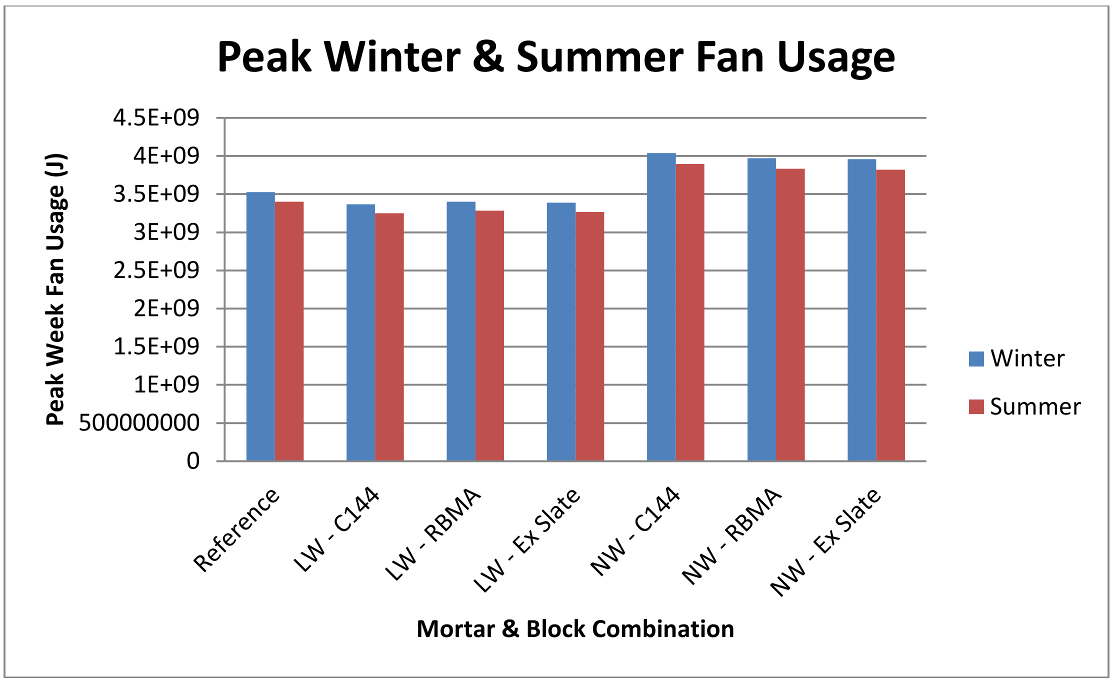

Figure 62: Phoenix, AZ strip mall concrete masonry model fan usage for peak summer and winter times

4.9 Seattle, Washington

4.9.1 Seattle, WA Reference Strip Mall Building Energy Consumption

The IECC classifies Seattle, Washington as Zone 4C, marine. Marine climates are described as a region that matches the following criteria: “a coldest month mean temperature between 27°F (-3°C) and 65°F (18°C), a warmest month mean of less than 72°F (22°C), at least 4 months with mean temperatures higher than 50°F (10°C), and a dry season in summer," (U.S. DOE, 2011). Also, the coldest month with the heaviest amount of precipitation must have three times the amount of precipitation of the month with the least amount of precipitation. In the United States, IECC zones 3 and 4 are located in the "C" moisture classification.

Figures 63, 64, and 65 represent the end-use percentages of heating, cooling, interior lighting, exterior lighting, interior equipment, and fans for the DOE reference model, lightweight concrete masonry model, and normal weight concrete masonry model simulations performed in Seattle. The largest consumer of energy in the Seattle simulations was heating with lighting coming in second. Heating ranges from 45.39% (DOE reference)-53.33% (normal weight). In contrast, cooling can almost be eliminated from this model. Cooling accounts for only 0.55% (lightweight C144 and normal weight C144)-0.82% (DOE reference) of the annual energy consumption end-use. This could be due to the amount of rain that Seattle receives annually.

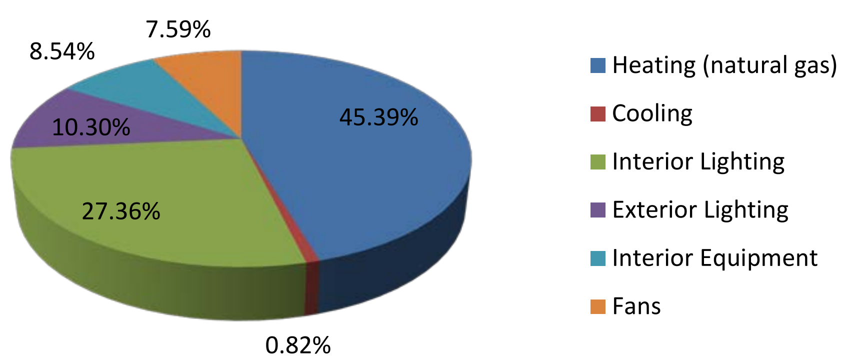

Figure 63: Seattle, WA strip mall DOE reference model annual energy consumption by end-use

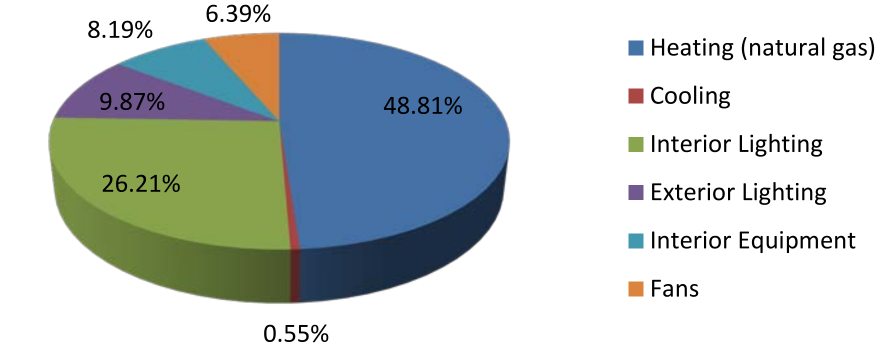

Figure 64: Seattle, WA strip mall lightweight C144 concrete masonry model annual energy consumption by end-use

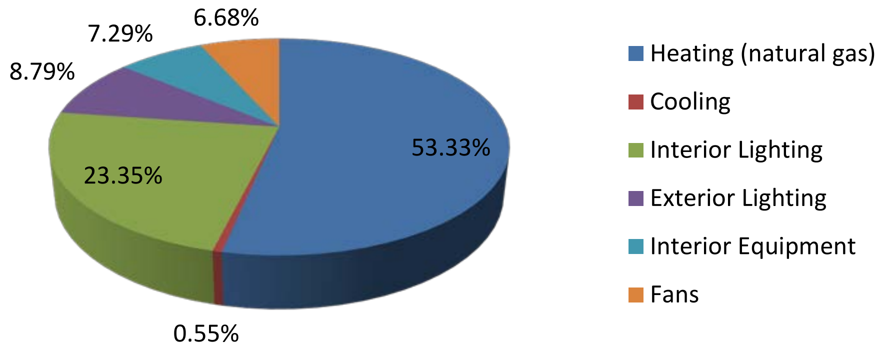

Figure 65: Seattle, WA strip mall normal weight C144 concrete masonry model annual energy consumption by end-use

4.9.2 Seattle, WA Strip Mall Building End-Use Performance with Recycled Aggregate Mortar

Figures 66, 67, 68, and 69 display annual energy consumption end-use percentages for lightweight RBMA, lightweight expanded slate, normal weight RBMA, and normal weight expanded slate mortar models. The leader in energy consumption for Seattle is heating. This is due to the cool and wet climactic conditions.

Heating amounts to nearly half of the annual end-use energy consumption for the lightweight models. The energy consumption increases from the lightweight C144 model to the lightweight recycled aggregate mortar models. These values equal 48.81% for the C144 model, 49.25% for the RBMA model, and 49.11% for the expanded slate model. Interior lighting is second highest in energy consumption for the lightweight models and ranges from 26.08% (expanded slate) to 26.21% (C144). There is a decrease from the lightweight C144 model to the recycled aggregate mortar models for interior lighting consumption. Even though the exterior lighting and interior equipment consume more energy these values stay the same regardless of the model. Therefore, these values will be disregarded for this analysis. Next, the most energy consumed is the overall fan usage. The fan energy consumption decreases from the lightweight C144 model to the recycled aggregate mortar models. 6.39% is consumed by the C144 model and 6.33% and 6.32% are consumed by the RBMA and expanded slate models. The smallest consumer of energy for the Seattle models is cooling and decreases from the lightweight C144 model to the recycled aggregate mortar models. These values range from 0.53% (RBMA) to 0.55% (C144).

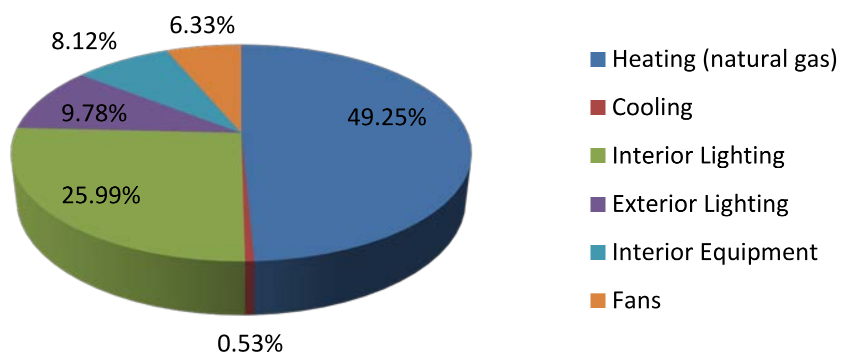

Figure 66: Seattle, WA strip mall lightweight concrete masonry model with RBMA mortar annual energy consumption by end-use

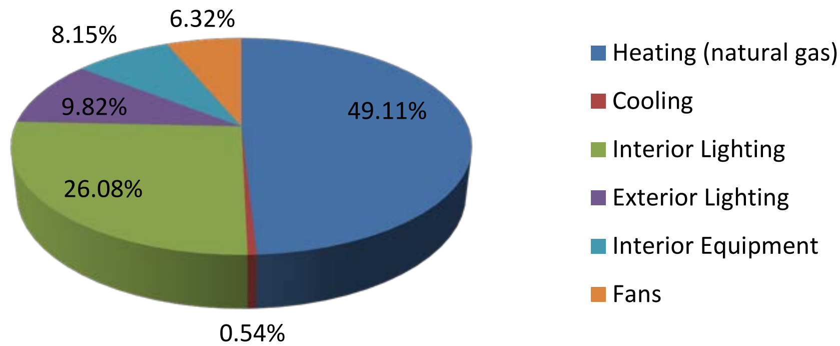

Figure 67: Seattle, WA strip mall lightweight concrete masonry model with expanded slate mortar annual energy consumption by end-use

The energy consumption for the normal weight and lightweight Seattle models deviate from each other more so than the other model locations. This could be due to the marine climactic conditions. Heating remains the largest consumer of energy at 53.33% for the normal weight C144 model, 53.46% for the normal weight RBMA model, and 53.40% for the normal weight expanded slate model. There is a slight increase in the heating percentages from the normal weight C144 model to the recycled aggregate mortar models which is similar to the pattern the lightweight models follow. The next largest consumer in end-use energy is interior lighting. Even though the amount of interior lighting used does not vary between models, it still amounts to a significant portion of the annual energy consumption. The interior lighting consumption for the normal weight models starts at 23.35% for the C144 model and increases to 23.38% for the RBMA model and 23.42% for the expanded slate model. Fan energy consumption also follows a similar pattern to that of the lightweight models and decreases from the C144 mode to the recycled aggregate models. These values range from 6.52% (expanded slate) to 6.68% (C144). Cooling accounts for a very small percentage of the overall consumption with the

C144 model equal to 0.55%, the RBMA model equal to 0.53%, and the expanded slate model equal to 0.52%.

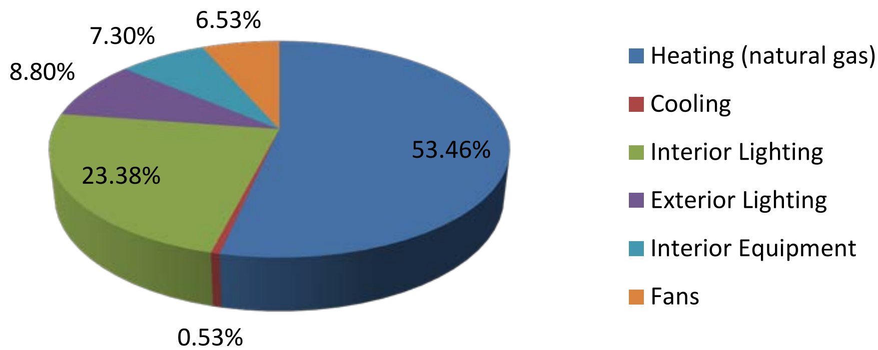

Figure 68: Seattle, WA strip mall normal weight concrete masonry model with RBMA mortar annual energy consumption by end-use

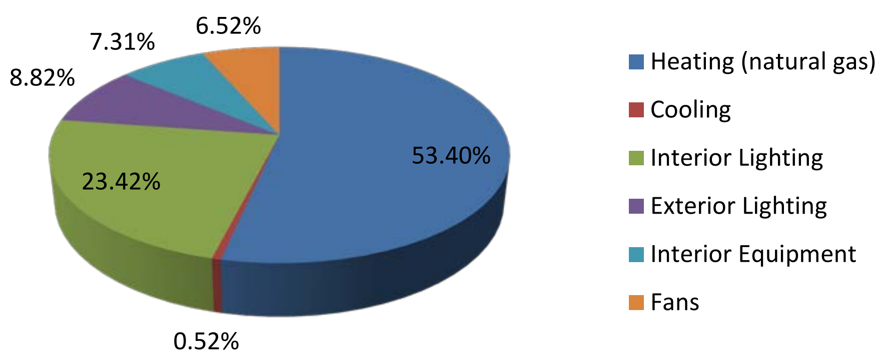

Figure 69: Seattle, WA strip mall normal weight concrete masonry model with expanded slate mortar annual energy consumption by end-use

Table 21 displays the EnergyPlus data obtained for annual building utility performance summary in Seattle for the DOE reference model, lightweight C144 model, lightweight recycled aggregate mortar models, normal weight C144 model, and normal weight recycled aggregate models. All of the lightweight models and the normal weight models increased in overall energy consumption from the DOE reference model. Of the three lightweight models, the C144 model performed the best with a decrease of 4.38% in energy consumption efficiency. Heating (natural gas) decreased by 12.23%, cooling increased by 30.33%, and fan consumption increase by 12.20% in energy efficiency. Even though cooling increased by 30.33% from the DOE reference model, a minimal impact was made to the total energy consumption efficiency due to the overall cooling consumption only equaling 0.55%. The other two lightweight models, RBMA and expanded slate, decreased in energy consumption efficiency by 5.25% and 4.90%.

The three normal weight models decreased in energy consumption efficiency approximately 16.50%-17.50%%. This is a significant increase in energy consumption and performed poorly in comparison to the DOE steel-frame reference model. The normal weight expanded slate model decreased the least amount at 16.81%. Heating (natural gas) decreased 37.43%, cooling increased 25.09%, and fan usage decreased 0.35% in energy efficiency. Like the lightweight C144 model, the large increase in cooling consumption efficiency does not affect the overall energy consumption because it only accounts for a total of 0.55% of the total end-use energy consumption. 17.13% and 16.99% decrease in energy consumption efficiency were experienced by the normal weight C144 and normal weight RBMA models.

Overall both models increased in end energy usage; the lightweight C144 model decreased by 4.38% in energy efficiency and the normal weight expanded slate model decreased by 16.81% in energy efficiency. Neither of these materials would be an appropriate energy efficient replacement to the DOE steel-frame reference model.

Table 21: Seattle, WA strip mall annual building utility performance summary

Energy End-Use	U.S. DOE Reference Model	Lightweight - C144 (< 105 lb/ft^3)		Lightweight - RBMA (< 105 lb/ft^3)		Lightweight - Ex Slate (< 105 lb/ft^3)		Normal Weight - C144 (> 125 lb/ft^3)		Normal Weight - RBMA (> 125 lb/ft^3)		Normal Weight - Ex Slate (> 125 lb/ft^3)	
	Energy (GJ)	Energy (GJ)	% Diff	Energy (GJ)	% Diff	Energy (GJ)	% Diff	Energy (GJ)	% Diff	Energy (GJ)	% Diff	Energy (GJ)	% Diff
Heating (natural gas)	793.83	890.91	-12.23%	906.48	-14.19%	900.85	-13.48%	1092.48	-37.62%	1093.77	-37.78%	1090.93	-37.43%
Cooling	14.31	9.97	30.33%	9.84	31.24%	9.82	31.38%	11.26	21.31%	10.8	24.53%	10.72	25.09%
Interior Lighting	478.41	478.41	0.00%	478.41	0.00%	478.41	0.00%	478.41	0.00%	478.41	0.00%	478.41	0.00%
Exterior Lighting	180.11	180.11	0.00%	180.11	0.00%	180.11	0.00%	180.11	0.00%	180.11	0.00%	180.11	0.00%
Interior Equipment	149.43	149.43	0.00%	149.43	0.00%	149.43	0.00%	149.43	0.00%	149.43	0.00%	149.43	0.00%
Fans	132.75	116.56	12.20%	116.43	12.29%	115.85	12.73%	136.78	-3.04%	133.51	-0.57%	133.22	-0.35%
Total	1748.84	1825.39	-4.38%	1840.7	-5.25%	1834.47	-4.90%	2048.47	-17.13%	2046.03	-16.99%	2042.82	-16.81%

An analysis was performed for the Seattle EnergyPlus models for an hourly assessment of heating and cooling usage over weeks that experience the highest and lowest temperatures. Comparisons of the models were analyzed by separating them into lightweight model results and normal weight model results then comparing them to the DOE reference model results for winter and summer. The hourly energy consumption results were then summed for a one week energy consumption analysis.

Values for the summary of heating consumption per hour for the first week of January are displayed in Table 22 for the lightweight concrete masonry models. The same information is displayed in Table 22 for the normal weight concrete masonry models. Seattle, Washington is a marine climate and has cold, humid winters which resulted in moderate hourly heat energy consumption.

Table 22: Seattle, WA heating energy usage week summary

Heating:Gas Week Sum (January 1st - January 8th) - Seattle							
	Reference	LW - C144	LW - RBMA	LW - Ex Slate	NW - C144	NW - RBMA	NW - Ex Slate
Total (GJ):	38.734	43.706	44.473	44.213	52.950	52.973	52.856
Hours Operating:	133	133	134	134	172	171	170
Percent Diff:		-12.83%	-14.82%	-14.15%	-36.70%	-36.76%	-36.46%

The lightweight C144 model and lightweight recycled aggregate mortar models exceeded the DOE reference model heating energy consumption for the entire first week of January by 5 GJ. The total energy consumptions for the lightweight models are equal to 43.706 GJ for the C144 model, 44.473 GJ for the RBMA model, and 44.213 GJ for the expanded slate model. The DOE reference model only consumed 38.734 GJ and required 133 hours of heating to maintain the temperature inside the facility. Weekly hour operation for the lightweight models are 133 hours for the C144 model and 134 hours for the RBMA and expanded slate models. Despite the similar number of hours spent heating the facility, the lightweight concrete masonry models are still less energy efficient than the DOE steel-frame reference model. A decrease in energy efficiency was seen from the DOE reference model and the lightweight concrete masonry models. A decrease in energy efficiency of 12.83% for the lightweight C144 model, 14.82% for the lightweight RBMA model, and 14.15% for the lightweight expanded slate models were experienced. The lightweight C144 model was the most energy efficient of the three lightweight models.

The normal weight models are in no way similar to the DOE reference model and the lightweight concrete masonry models. The weekly sum of the hourly heating usage far exceeds the lightweight and DOE reference models for the normal weight models at 52.950 GJ for the C144 model, 52.973 GJ for the RBMA model, and 52.856 GJ for the expanded slate model. Not only does the amount of energy required exceed the DOE reference model and lightweight models but the number of hours required to heat the facility exceeds the C144 model by 38 hours. 172 hours are required for the normal weight C144 model, 171 hours are required for the normal weight RBMA model, and 170 hours are required for the normal weight expanded slate model. More than an entire day is required to keep the facility heated with normal concrete masonry construction instead of the DOE steel-frame reference model construction. The energy efficiency significantly decreased from the DOE reference model to the normal weight concrete masonry models; the normal weight C144 model decreased by 36.70%, the normal weight RBMA model decreased by 37.76%, and the normal weight expanded slate model decreased by 36.46%. Overall, the normal weight expanded slate performed the best.

Both the lightweight models and normal weight models exceed the energy usage of the DOE reference model however, the lightweight models are much closer in weekly energy usage for the first week of January. The excessive required energy and hours to heat the facility constructed with normal weight concrete masonry variations automatically makes the normal weight models a poor choice for energy efficiency.

The cooling energy consumption for the first week of summer, July 1st to July 8th, for Seattle, Washington was recorded hourly for the lightweight, the normal weight, and the DOE reference models. Table 23 displays a weekly summary of the hourly consumption for the lightweight models, the normal weight models, and the DOE reference model. Seattle, Washington has a marine climate and experiences cool to warm summer which greatly affects the overall cooling energy consumption.

Table 23: Seattle, WA cooling energy usage week summary

Cooling:Electricity Week Sum (July 1st - July 8th) - Seattle							
	Reference	LW - C144	LW - RBMA	LW - Ex Slate	NW - C144	NW - RBMA	NW - Ex Slate
Total (GJ):	0.412	0.263	0.258	0.257	0.301	0.286	0.282
Hours Operating:	38	29	28	28	30	29	29
Percent Diff:		36.07%	37.34%	37.52%	26.99%	30.58%	31.46%

The lightweight concrete masonry models outperformed the DOE reference model during the first week of July. Table 23 shows that during peak summer temperatures, the DOE reference model consumes more energy than the lightweight model while cooling the strip mall. Also, the cooling system hardly operated during the warmest time of the year. The lightweight models consumed 0.263 GJ over 29 hours for the C144 model, 0.258 GJ over 28 hours for the RBMA model, and 0.257 GJ over 28 hours for the expanded slate model for the cooling energy consumption. In comparison, the DOE reference model consumed 0.412 GJ over 38 hours. The lightweight models consume just less than half of the amount of energy required to cool the building over one week for the DOE reference model. The lightweight models increased in energy efficiency when compared to the DOE reference model. The lightweight C144 model increased by 36.07%, the lightweight RBMA model increased by 37.34%, and the lightweight expanded slate model increase by 37.52%. The expanded slate model had the highest increase in energy efficiency.

Like the lightweight concrete masonry models, the normal weight concrete masonry models outperformed the DOE reference model. The normal weight models consumed 0.301 GJ over 30 hours for the C144 model, 0.286 GJ over 29 hours for the RBMA model, and 0.282 GJ over 29 hours for the expanded slate model. Table 24 shows the total energy consumption over the first week of July. The DOE reference model consumes more energy than the normal weight models during peak cooling energy consumption times of the week. Overall, the normal weight concrete masonry models consume less energy and operate for fewer hours throughout the week. The normal weight expanded slate model had the highest increase in energy efficiency at 31.46% with the normal weight RBMA and C144 models following at 30.58% and 26.99%.

After analyzing the lightweight and normal weight concrete masonry models, it can be concluded that both categories of models are more energy efficient than the DOE reference model. The lightweight and normal weight models all consume less energy while cooling the strip mall and require less hours of operation. For both the lightweight and normal weight models, the recycled aggregate mortar models outperformed the C144 models. The DOE steel-frame reference model build envelope would be a poor choice compared to the lightweight and normal weight models. Both of these categories of models perform well in Seattle, Washington climate conditions.

The next analysis was performed on energy consumption for fan usage during peak winter and summer temperatures. Figure 70 shows the total energy consumed from January 1st to January 8th and July 1st to July 8th for each of the seven strip mall models. During the winter the fan energy consumption was greater for all of the models. The percent difference in fan energy consumption from summer to winter ranges from 3.88% for the DOE reference model to 5.03% for the normal weight models. All of the normal weight models consume more energy than the DOE reference model and all of the lightweight models consume less energy than the DOE reference model.

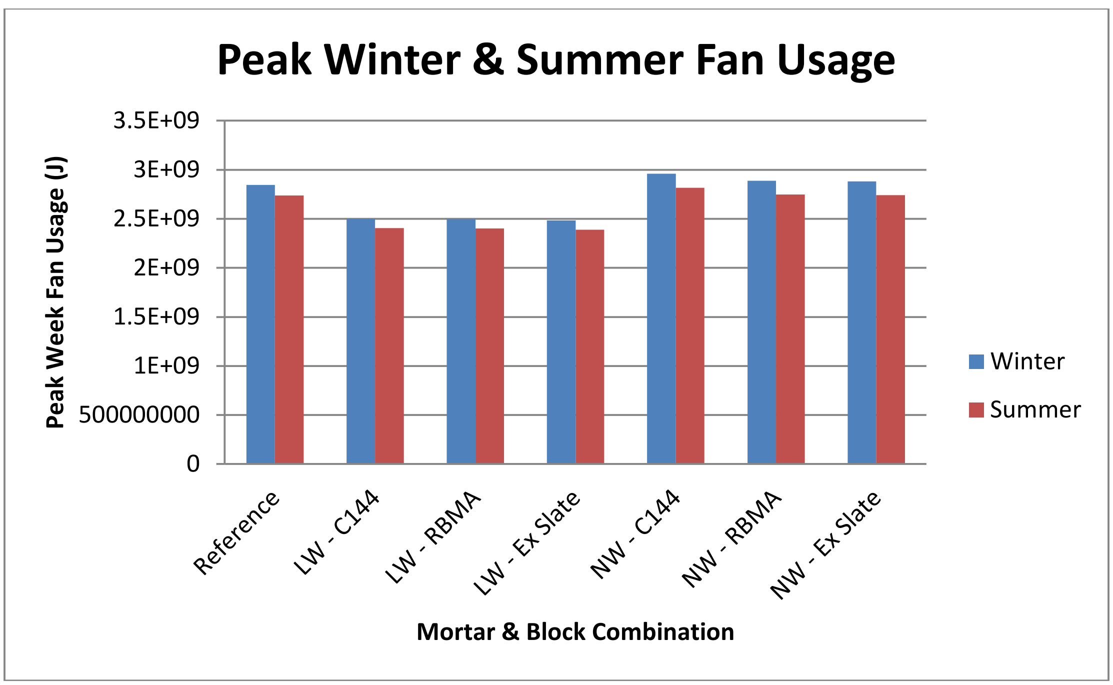

Figure 70: Seattle, WA strip mall concrete masonry model fan usage for peak summer and winter times

4.10 Total Annual Facility Cost Analysis

Utility costs are necessary for analyzing the effectiveness of implementing energy efficient technologies in a facility. The only two forms of energy analyzed for the models are electricity and natural gas. Typically, energy rate schedules are used to calculate utility costs but due to the variability in the data across the United States and from year to year it would be very difficult to obtain from each census division (NREL, 2011). Current utility prices are not reflected in EnergyPlus™ as the data was obtained in 2004 from the Tariff Analysis Project and local utilities.

Taxes on utilities vary greatly between cities, county governments, and energy providers. Even though there is a wide variation in taxation, taxes are an integral part of energy costs in the commercial facility sector and are included in the EnergyPlus models (NREL, 2011). EnergyPlus calculates tax rates by assuming that energy taxes and state sales tax are equal in addition to adding 2% to cover city and county taxes.

In order to discuss the efficiency of implementing concrete masonry into the building envelope, the annual utility cost savings between the DOE reference model and the concrete masonry models were analyzed for all seven locations. The total facility annual utility costs for each model are shown in Figure 71. In order to clarify the data presented in Figure 71, Table 24 was created to show the annual costs specific to each model. Another form of analysis was to compare the total energy consumption in gigajoules that was associated to the costs displayed in Figure 71 and Table 24. Figure 72 and Table 25 display the total annual energy consumption for each city.

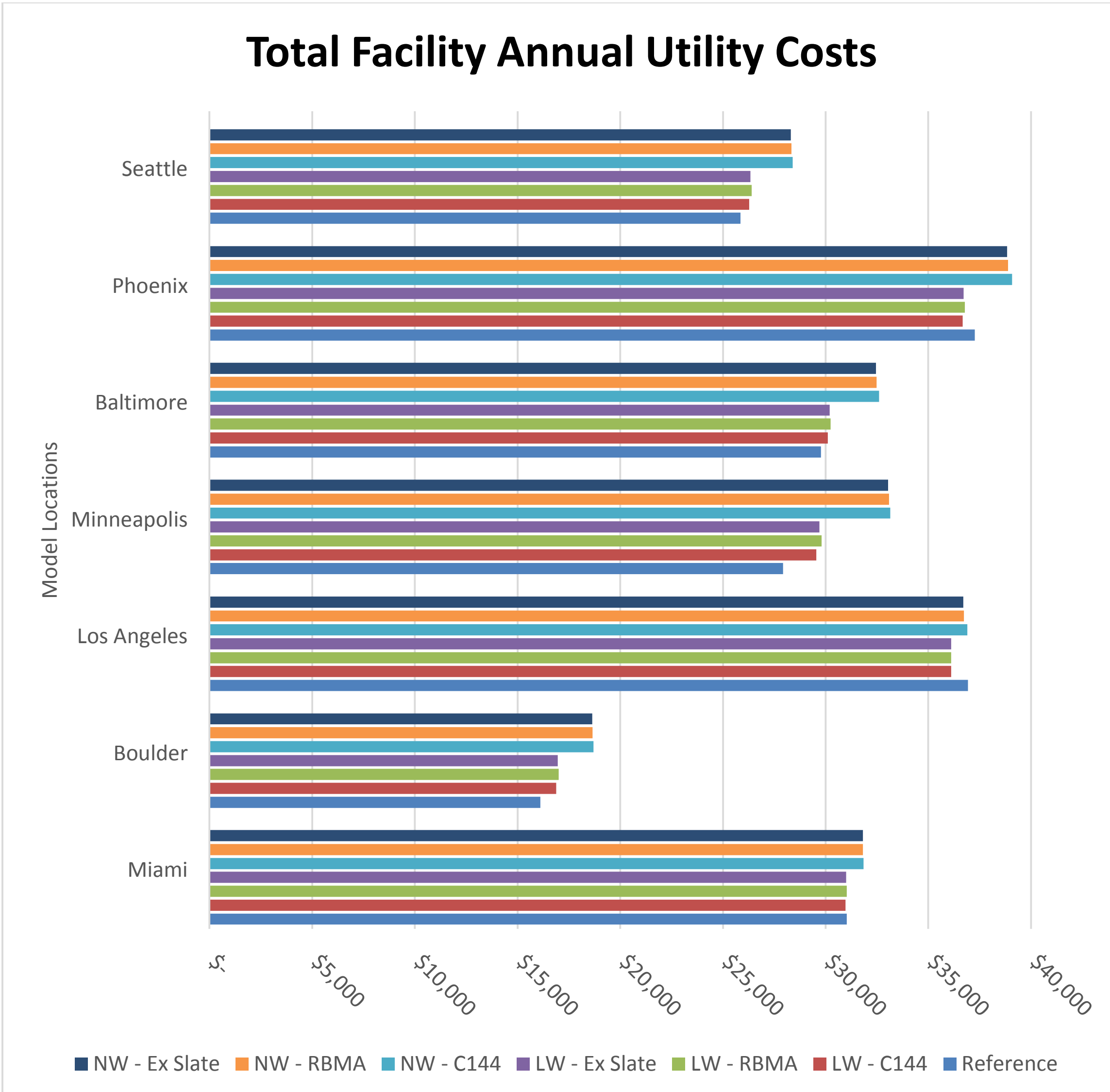

Figure 71: Total facility annual utility costs

Table 24: Total facility annual utility costs for each model in GJ

Location:	Reference	LW - C144	LW - RBMA	LW - Ex Slate	NW - C144	NW - RBMA	NW - Ex Slate
Miami	$31029.53	$30966.68	$31028.25	$31001.64	$31852.05	$31822.00	$31811.86
Boulder	$16103.17	$16883.42	$17007.64	$16953.03	$18700.58	$18655.80	$18634.25
Los Angeles	$36936.55	$36114.66	$36118.32	$36106.30	$36901.04	$36735.58	$36709.65
Minneapolis	$27922.28	$29544.20	$29805.89	$29700.90	$33148.96	$33088.11	$33036.43
Baltimore	$29772.85	$30107.16	$30238.38	$30191.54	$32595.73	$32479.98	$32449.36
Phoenix	$37257.68	$36671.24	$36785.46	$36722.76	$39085.80	$38883.52	$38832.50
Seattle	$25860.92	$26273.45	$26400.04	$26340.39	$28403.06	$28340.06	$28308.93

In comparing the total facility annual utility cost data, it can be seen in five of the seven locations concrete masonry building envelopes are less cost efficient than the basic steel-frame building envelope. The two instances in which the concrete masonry building envelope is more cost efficient is in Phoenix, Los Angeles, and Miami. In the model located in Phoenix, there is an annual energy savings of $586.44 if the lightweight C144 concrete masonry envelope is used. This amounts to a 1.60% savings annually of the total cost of the lightweight C144 concrete masonry envelope. Implementing all of the concrete masonry envelopes on the strip mall model is also more cost effective in Los Angeles; however, both the lightweight and normal weight building envelopes are more cost effective than the steel-frame envelope. An annual savings of $821.89 can be achieved with the use of a lightweight concrete masonry envelope which amounts to a 2.28% overall savings. A similar situation is seen with the normal weight concrete masonry envelope. An annual savings of $35.51 and a 0.10% overall savings. It would be much more cost effective to implement the lightweight concrete masonry envelopes in the strip mall in both Phoenix and Los Angeles. The savings for the normal weight concrete masonry in Los Angeles is almost negligible. A similar situation occurs with the costs for Miami. There is an annual energy savings of $21.89 and a 0.09% overall savings for the lightweight expanded slate model. The amount of money saved is almost negligible due to such little money being saved.

Figure 72 and Table 25 show the annual energy consumption in both graphical form and numerical form. It was observed that the cost and energy usage do not always have a linear relationship. For example, the Miami, Florida DOE reference model cost $31,029.53 while consuming 1,335.30 GJ of energy over the course of the year but the lightweight C144 model cost $30,996.68 while consuming 1,335.88 GJ of energy over the course of the year. This difference could be a result of the local natural gas costs and electricity costs.

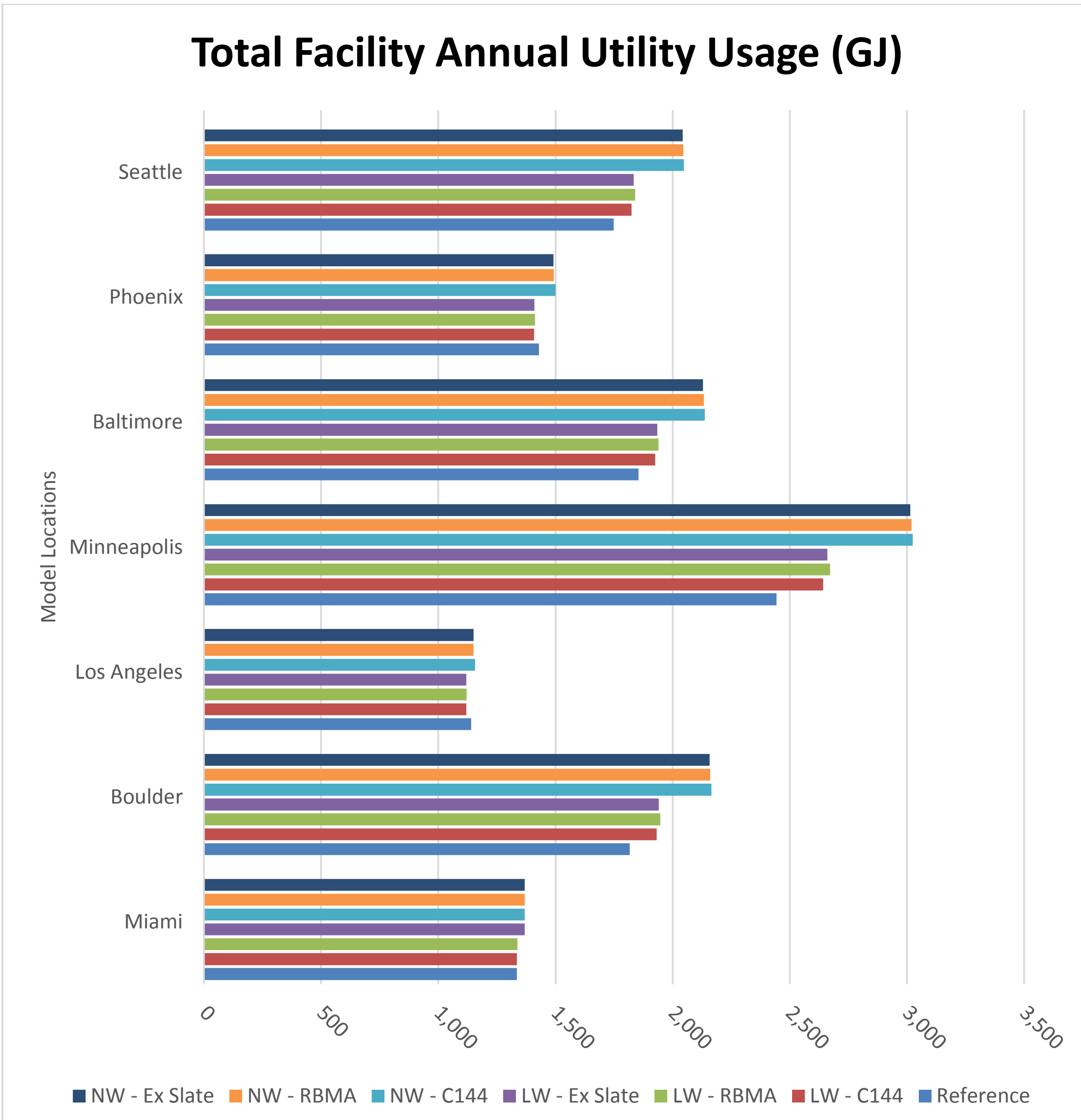

Figure 72: Total facility annual utility usage

Table 25: Total facility annual utility usage for each model in GJ

Location:	Reference	LW - C144	LW - RBMA	LW - Ex Slate	NW - C144	NW - RBMA	NW - Ex Slate
Miami	1,335.30	1,335.88	1,337.81	1,368.69	1,368.69	1,368.66	1,368.29
Boulder	1,817.08	1,932.31	1,947.80	1,940.66	2,166.17	2,160.60	2,157.82
Los Angeles	1,139.82	1,119.94	1,120.56	1,119.65	1,156.45	1,150.93	1,149.95
Minneapolis	2,443.70	2,643.22	2,672.07	2,660.88	3,024.59	3,020.46	3,015.31
Baltimore	1,854.19	1,926.29	1,939.38	1,935.26	2,137.54	2,133.04	2,130.40
Phoenix	1,429.14	1,408.43	1,412.64	1,410.11	1,500.46	1,493.31	1,491.41
Seattle	1,748.84	1,825.39	1,840.70	1,834.47	2,048.47	2,046.03	2,042.82

After studying the results, it can be concluded that each concrete masonry model and the respective recycled aggregate mortar models vary in performance for each location across the United States. In situations where a significant amount of heating was required, the concrete masonry building envelope decreased in energy efficiency. The only location where the concrete masonry envelope performed better than the DOE reference model was in Miami, FL for the lightweight concrete masonry models. The concrete masonry building envelopes performed best when cooling was required during the summer. All of the lightweight model variations improved in energy efficiency for cooling from the DOE reference model except for Phoenix, AZ and Miami, FL. Although these models did not perform as well, the loss in energy efficiency was almost negligible.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The United States Department of Energy (DOE) reported in 2012 that the building industry is the largest consumer of natural resources and electricity. In order to address the impact of the construction industry on the environment, use of raw, virgin aggregate and energy efficiency must improve. Commercial building energy consumption is currently being addressed by the building sector by investigating new materials, building envelopes, and energy efficiency best practices.

Growth in the new construction sector places a higher demand for natural aggregate resulting in an escalation in natural aggregate costs. The focus of this research is to determine the impact on specific heat capacity and thermal conductivity using recycled demolition waste aggregates in masonry mortar and grout applications. A possible solution to reduce demand on natural aggregates is the use of expanded slate and recycled brick aggregate in masonry mortar applications.

In this study, the thermal properties of the recycled aggregate mortar were obtained from previous research in order to create a comparative analysis between the Department of Energy strip mall steel-frame model, normal weight and lightweight concrete masonry models, and normal weight and lightweight recycled aggregate models in the EnergyPlus BESP. The objectives achieved by this study were:

- A model using building energy simulation programs (BESP) for a concrete masonry structure using recycled aggregates was developed and validated by creating a model in EnergyPlus and comparing the results to the DOE results,
- Models for each masonry mortar aggregate were successfully developed and simulated,
- A comparative analysis of annual energy consumption by end-use, the annual building utility performance summary, the heating, cooling, and fan energy usage for peak winter and summer weeks, and the total annual cost and utility usage were performed and results indicated that the recycled aggregate mortar models performed as well or better than the lightweight and normal weight C144 masonry systems.

The model results show that in Miami, FL the concrete masonry models did not perform as well as the DOE reference model; however, the recycled aggregate mortar models performed as well as and sometimes better than the lightweight and normal weight concrete masonry models. During the peak summer week, the normal weight expanded slate and normal weight C144 models decreased in energy efficiency by 7.60% and 7.80%. A similar outcome was observed for the peak winter week also. The normal weight expanded slate and normal weight C144 model decreased in energy efficiency by 17.45% and 20.82%. The lightweight C144 model proved to be most energy efficient for both heating and cooling. The lightweight expanded slate model actually increased in energy efficiency by 2.89% while heating.

In Boulder, CO, the model results showed that the lightweight concrete masonry models were more energy efficient than the DOE reference model for cooling energy consumption. Even though the normal weight models were less energy efficient than the DOE reference model, the normal weight expanded slate model performed the best. For heating energy efficiency, the normal weight and lightweight models all decreased in energy efficiency. The lightweight C144 model and the normal weight expanded slate models performed the best from the respective categories.

In contrast to the other locations, Los Angeles, CA cooling energy efficiency improved from the DOE reference model to the lightweight and normal weight concrete masonry models. The lightweight RBMA model and normal weight expanded slate model increased in energy efficiency of 31.93% and 33.04% and are more energy efficient than the other models. For the heating energy consumption, the lightweight C144 and normal weight C144 models were the most energy efficient at an 11.58% and 34.14% decrease in energy efficiency. Even though there was a decrease in the energy efficiency of heating, the recycled aggregate mortar models were very close in energy consumption to the rest of the models.

For the Minneapolis, MN results, the lightweight and normal weight models for cooling energy consumption performed very different. All of the lightweight models increased in energy efficiency with the lightweight C144 model at 2.29% being the most energy efficient. In contrast, the normal weight models decreased in energy efficiency. The normal weight expanded slate model being the most energy efficient decreased 12.38% in energy efficiency. The heating energy consumption results were different in that all of the lightweight a normal weight models decreased in energy efficiency. The lightweight C144 model and normal weight expanded slate models were the most energy efficient with a decrease of 13.79% and 36.59% in energy efficiency.

Baltimore, MD experienced a slight deviation in energy efficiency for cooling energy consumption from the DOE reference model to the normal weight and lightweight models. The lightweight models all increased in energy efficiency with the lightweight C144 model being the most energy efficient at a 4.73% increase. The normal weight expanded slate model was the most energy efficient normal weight model with a 3.80% decrease in energy efficiency. All of the concrete masonry models decreased in energy efficiency for the concrete masonry models. The lightweight C144 model and normal weight expanded slate model were the most energy efficient options with a13.51% and 38.24% decrease in energy efficiency.

A percent decrease was experienced in Phoenix, AZ for both the cooling and heating energy efficiency. The most energy efficient models for the cooling energy efficiency were the lightweight C144 and normal weight expanded slate models. These models experienced a 0.18% and 15.36% decrease in energy efficiency respectively. The heating energy consumption performed similarly except that the decrease in energy efficiency was greater. The lightweight C144 model and the normal weight expanded slate models performed the best with a decrease of 6.95% and 18.83% energy efficiency. Although there was a decrease in energy efficiency for all of the models, the recycled aggregate mortar models performed as well or better than the C144 concrete masonry models.

Cooling energy efficiency in Seattle, WA experienced the highest increase in energy efficiency of all of the model locations. The lightweight expanded slate and normal weight expanded slate models were the most energy efficient with a 37.52% and 31.46% increase in energy efficiency for cooling energy consumption. In contrast, heating energy consumption models all decreased in energy efficiency. The lightweight C144 and normal weight expanded slate models were the most energy efficient experiencing a 12.83% and 36.46% decrease in energy efficiency.

After studying the results, it can be concluded that each concrete masonry model and the respective recycled aggregate mortar models vary in performance for each location across the United States. In situations where a significant amount of heating was required, the concrete masonry building envelope decreased in energy efficiency. The only location where the concrete masonry envelope performed better than the DOE reference model was in Miami, FL for the lightweight concrete masonry models. The concrete masonry building envelopes performed best when cooling was required during the summer. All of the lightweight model variations improved in energy efficiency for cooling from the DOE reference model except for Phoenix, AZ and Miami, FL. Although these models did not perform as well, the loss in energy efficiency was almost negligible.

The results showed that the RBMA and expanded slate models consistently performed as well, if not better than the lightweight and normal weight C144 models. By replacing sand with RBMA and expanded slate aggregate in mortar mixes, a more environmentally conscious material has been created. Recycled aggregate mortar will help to reduce demolition waste aggregates, maintain competitive aggregate costs, decrease the need for new quarrying sites, and contribute to a more sustainable building envelope design.

5.2 Future Work

Given the results, a more involved regional analysis should be performed due to the variance in performance of the concrete masonry C144 models and the recycled aggregate mortar variations across the United States. A regional focus study would allow for a more comprehensive analysis of how the concrete masonry C144 models and the recycled aggregate mortar models perform in similar climactic conditions. Also, analyzing the true energy costs in a regionally focused study would provide a more accurate cost estimate. An additional type of analysis that should be performed is the cost of recycled aggregates in the region specific to each model. The availability and cost of the recycled aggregate materials will determine whether it is a cost effective material for practical applications in construction. Lastly, a life cycled cost analysis (LCCA) should be performed on the entire building to better understand true energy savings over time. In order to determine the sustainability and practicality of the material, additional cost and performance analyses need to be conducted.

REFERENCES

ASTM Standard C33, 2003, "Specification for Concrete Aggregates," ASTM International, West Conshohocken, PA, 2012, DOI: 10.1520/C0033-03, www.astm.org.

ASTM Standard C109, 2013, “Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens),” ASTM International, West Conshohocken, PA, 2012, DOI: 10.1520/C0109_C0109M-13, www.astm.org.

Buhl, W. F., Crawley, D.B., Fisher, D. E., Glazer, J., Huang, Y. J., Lawrie, L. K., Liesen, R. J., Pedersen, C. O., Strand, R. K., Winkelmann, F. C., and Witte, M. J. (April 2001). “EnergyPlus: creating a new-generation building energy simulation program.” Energy and Buildings, 33(4), 319-331.

Cavalline, T. L., and Weggel, D. C. (2013). “Recycled Brick Masonry Aggregate Concrete” Structural Survey 31(3), 160-180.

Crawley, D.B. (February 16, 2010). “EnergyPlus: DOE’s Next Generation Simulation Program.” <http://www1.eere.energy.gov/buildings/pdfs/eplus_webinar_02-16-10.pdf> (Sept. 28, 2013).

Crawley, D.B. (1998). “Which Weather Data Should You Use for Energy Simulations of Commercial Buildings?” American Society of Heating, Refrigerating, and Air-Conditioning Engineers, TO-98-2-2: 1-5.

Crawley, D. B., Lawrie, L. K., Pedersen, C. O., and Winkelmann, F. C. (April 2000). “EnergyPlus: Energy Simulation Program.” American Society of Heating, Refrigerating, and Air-Conditioning Engineers, 42(4), 49-56.

Environmental Council of Concrete Organizations (ECCO). (1999). “Recycling concrete and masonry.” Informational Bulletin EV-22.

Environmental Protection Agency (31 October 2012) “Construction and Demolition (C&D) Debris.” < http://www.epa.gov/reg3wcmd/solidwastecd.html> (Feb. 20, 2014).

Etxeberria, M., Marí, A. R., Vázquez, E. (2007). “Recycled aggregate concrete as structural material.” Materials and structures, 40(5), 529-541.

Gilpin, R. R., Hyun, H., and Menzie, D. W. (2004). “Recycling of construction debris as aggregate in the Mid-Atlantic Region, USA.” Resources, Conservation, and Recycling, 42(3), 275-294.

Goonan, T. G. (February 2000). “USGS Fact Sheet: Recycled Aggregates – Profitable Resource Conservation.” United States Geological Survey, FS–181–99.

Graber, D. W., Lang, N. R., Mariscal, G., Thompson, J. J., and Witthuhn, T. (2012). “Thermal Catalog of Concrete Masonry Assemblies.” National Concrete Masonry Association, 2, 6-9.

Graber, D. W., Lang, N. R., Mariscal, G., and Thompson, J. J. (2010). “Thermal Catalog of Concrete Masonry Assemblies.” National Concrete Masonry Association, 1, 1.

Graphic Maps. “Maps of the United States of America.” <http://www.worldatlas.com/webimage/testmaps/usanames.gif> (July 16, 2014).

Ibarra, D. and Reinhart, C. (Sept. 30, 2009). “Building Performance Simulation for Designers – Energy.” <http://www.gsd.harvard.edu/research/gsdsquare/Publications/GettingStartedWithDesignBuilderEnergyPlus.pdf> (Sept. 28, 2013).

Khalaf, F. and DeVenny, A. (2004). “Recycling of Demolished Masonry Rubble as Coarse Aggregate in Concrete: Review.” Journal of Materials in Civil Engineering, 16(4), 331-340.

Jha, K. N., Misra, S., and Rao, A. (March 2007). “Use of aggregates from recycled construction and demolition waste in concrete.” Resources, Conservation, and Recycling, 50(1), 71-81.

Leadership in Energy and Environmental Design. “Frequently Asked Questions.” <http://www.usgbc.org/Docs/LEEDdocs/LEEDfaq-materials2.pdf> (Sept. 15, 2013).

Ledesma, E.F., Jiménez, J.R., Fernández, J.M., Galvín, A.P., Agrela, F., and Barbudo, A. (September 2014). “Properties of masonry mortars manufactured with fine recycled concrete aggregates.” Construction and Building Materials, 71(2014), 289-298.

Liu, B., Jarnagin, R.E., Winiarski, D.W., Jiang, W., McBride, M., and Crall, G.C. (September 2006). “Technical Support Document: Development of the Advanced Energy Design Guide for Small Retail Buildings.” Pacific Northwest National Laboratory, PNNL-16031.

Martínez, I., Etxeberria, M., Pavón, E., and Díaz, N. (September 2013). “A comparative analysis of the properties of recycled and natural aggregate in masonry mortars.” Construction and Building Materials, 49(2013), 384-392.

National Renewable Energy Laboratory. “OpenStudio.” <http://openstudio.nrel.gov/> (Oct. 1, 2013).

National Renewable Energy Laboratory (February 2011). “U.S. Department of Energy Commercial Reference Building Models of the National Building Stock.” National Renewable Energy Laboratory, NREL/TP-550-46861.

Peña, L.V. (2012). “Phase Change Material (PCM) – Enhanced Building Envelopes for Energy-Efficient Commercial Buildings.” Master’s Thesis, The University of North Carolina at Charlotte.

Radford, P.D. (2014). “Compressive and Thermal Performance of Recycled Aggregate Mortar.” Master’s Thesis, The University of North Carolina at Charlotte.

Tam, C.M., and Tam, V. W. Y. (June 2006). “A review on the viable technology for construction waste recycling.” Resources, Conservation, and Recycling, 47(3), 209-221.

U.S. Army Corps of Engineers (September 2004). “Reuse of Concrete Materials from Building Demolition.” Public Works Technical Bulletin, 200-1-27.

U.S. Department of Energy (30 April 2013). "About Energy Plus." <http://apps1.eere.energy.gov/buildings/energyplus/energyplus_about.cfm> (Sept. 26, 2013).

U.S. Department of Energy (July 2013). “About the Commercial Buildings Integration Program.” Building Technologies Office. <http://www1.eere.energy.gov/buildings/commercial/about.html> (Sept. 5, 2013).

U.S. Department of Energy (March 2012). "Buildings Sector Energy Consumption." Buildings Energy Data Book, <http://buildingsdatabook.eren.doe.gov/TableView.aspx?table=1.1.3> (Sept 3, 2013).

U.S. Department of Energy, (August 2010). "Building Technologies Program: Guide to Determining Climate Regions by County." <http://apps1.eere.energy.gov/buildings/publications/pdfs/building_america/ba_climateguide_7_1.pdf.> (July 10, 2014).

U.S. Department of Energy (July 2013). "Commercial Reference Buildings." <http://energy.gov/eere/buildings/commercial-reference-buildings> (Nov 20, 2014).

U.S. Department of Energy (September 25, 2014). “EnergyPlus Engineering Reference.” <http://apps1.eere.energy.gov/buildings/energyplus/cfm/inputs/> (Nov 20, 2014).

U.S. Department of Energy (October 2013). “EnergyPlus Example File Generator.” EnergyPlus Energy Simulation Software, <http://apps1.eere.energy.gov/buildings/energyplus/cfm/inputs/> (July 2, 2014).

U.S. Department of Energy (March 2012). "Commercial Sector Energy Consumption." Buildings Energy Data Book, <http://buildingsdatabook.eren.doe.gov/TableView.aspx?table=3.1.1> (Sept 3, 2013).

U.S. Energy Information Administration (April 2013). "Annual Energy Outlook 2013." DOE/EIA-0383(2013).

U.S. Green Building Council (2011). "Green Building Facts." <http://www.usgbc.org/Docs/Archive/General/Docs18693.pdf> (August 26, 2013).

Waide, P., Amann, Jennifer T., and Hinge, A. (July 2007). "Energy Efficiency in the North American Existing Building Stock." Energy Efficiency Series, Paris Cedex, France.

APPENDIX A: RECYCLED AGGREGATE MODEL INPUTS

Table A-1: EnergyPlus normal weight recycled aggregate inputs

	RBMA	Expanded Slate	NW	Weighted Average (RBMA)	Weighted Average (Ex Slate)
Conductivity (W/m-K)	1.33	1	1.13	1.139	1.124
Density (kg/m3)	1772.39	1705.71	2180	2160.893	2157.768
Specific Heat (J/kg-K)	3148	3057	920	1024.438	1020.172
Thickness (m)	0.009525	0.009525	0.193675	0.203	0.203

Table A-2: EnergyPlus light weight recycled aggregate inputs

	RBMA	Expanded Slate	LW	Weighted Average (RBMA)	Weighted Average (Ex Slate)
Conductivity (W/m-K)	1.33	1	0.33	0.377	0.361
Density (kg/m3)	1772.39	1705.71	1380	1398.393	1395.268
Specific Heat (J/kg-K)	3148	3057	880	986.313	982.047
Thickness (m)	0.009525	0.009525	0.193675	0.203	0.203

APPENDIX B: HOURLY HEATING AND COOLING GRAPHS

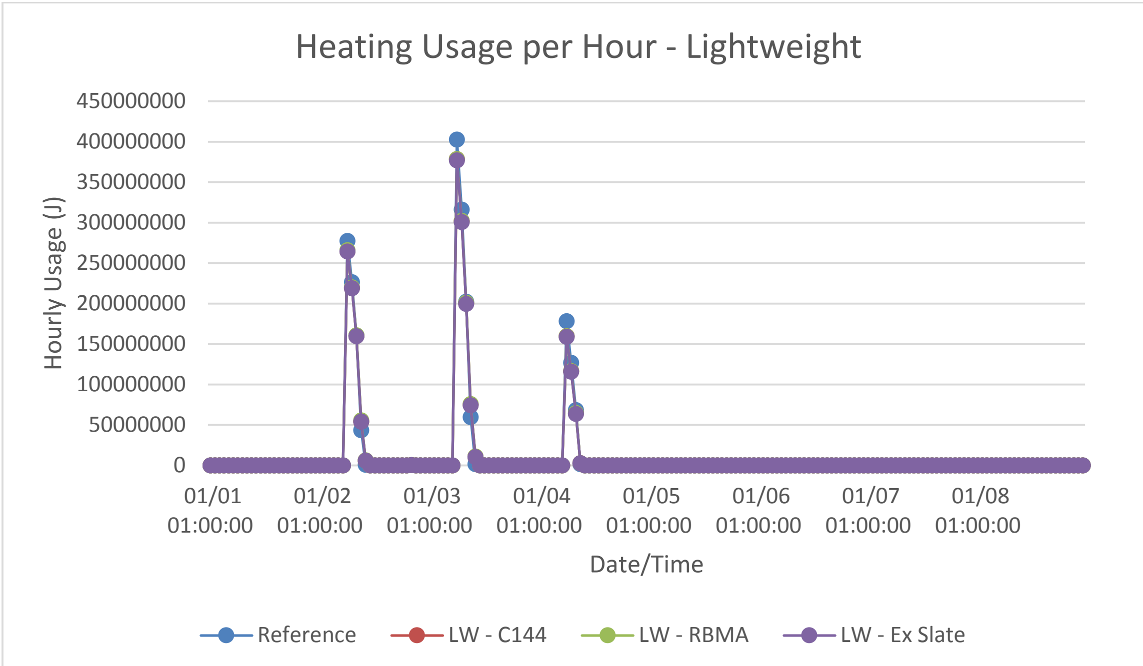

Figure B-1: Miami, FL lightweight models hourly heating energy consumption in winter

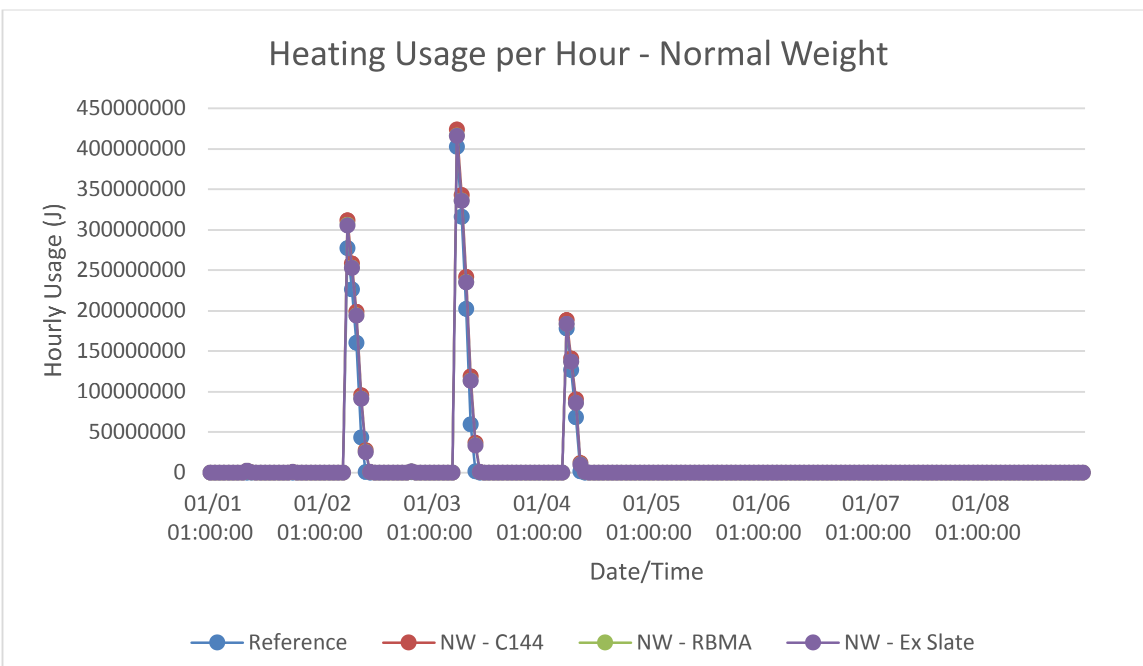

Figure B-2: Miami, FL normal weight models hourly heating energy consumption in winter

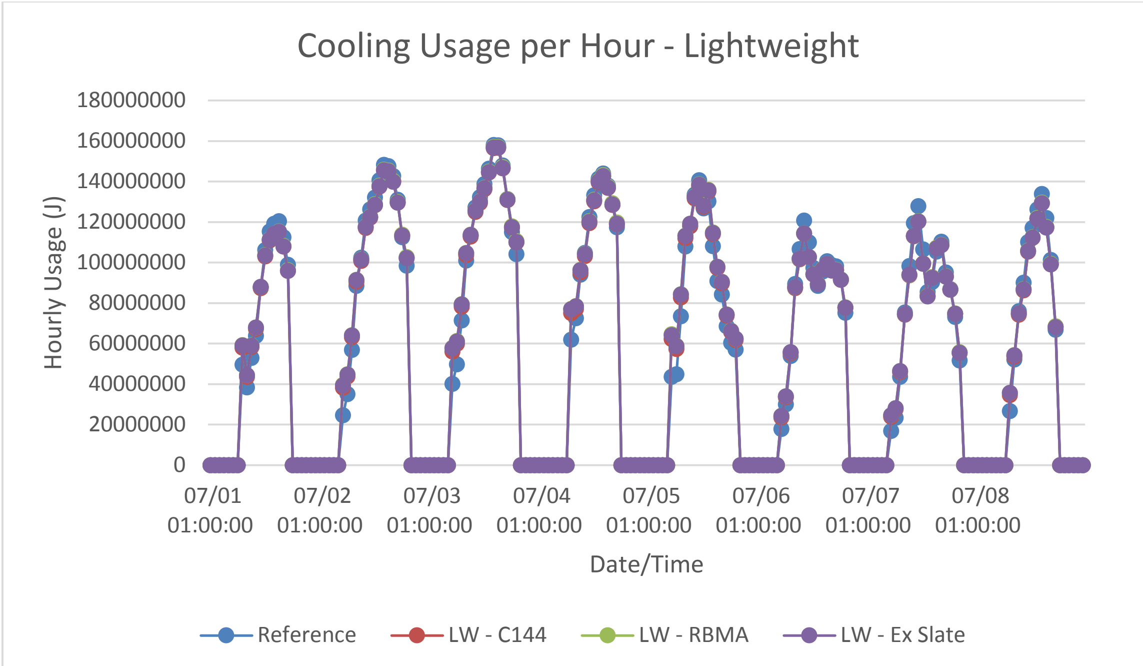

Figure B-3: Miami, FL lightweight models hourly cooling energy consumption in summer

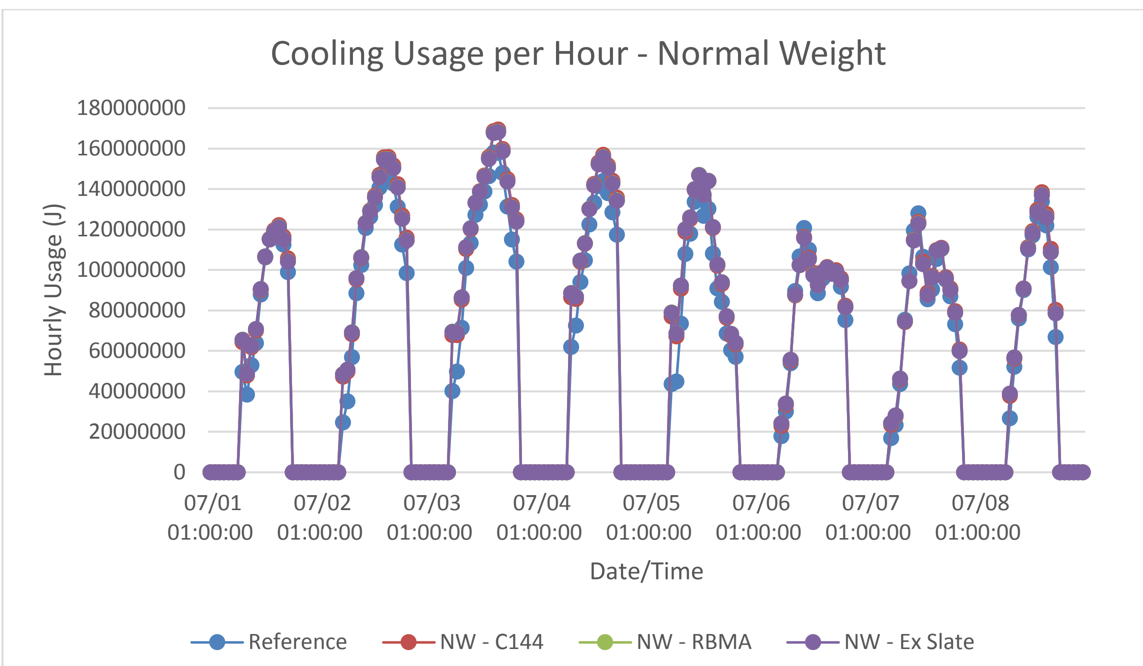

Figure B-4: Miami, FL normal weight models hourly cooling energy consumption in summer

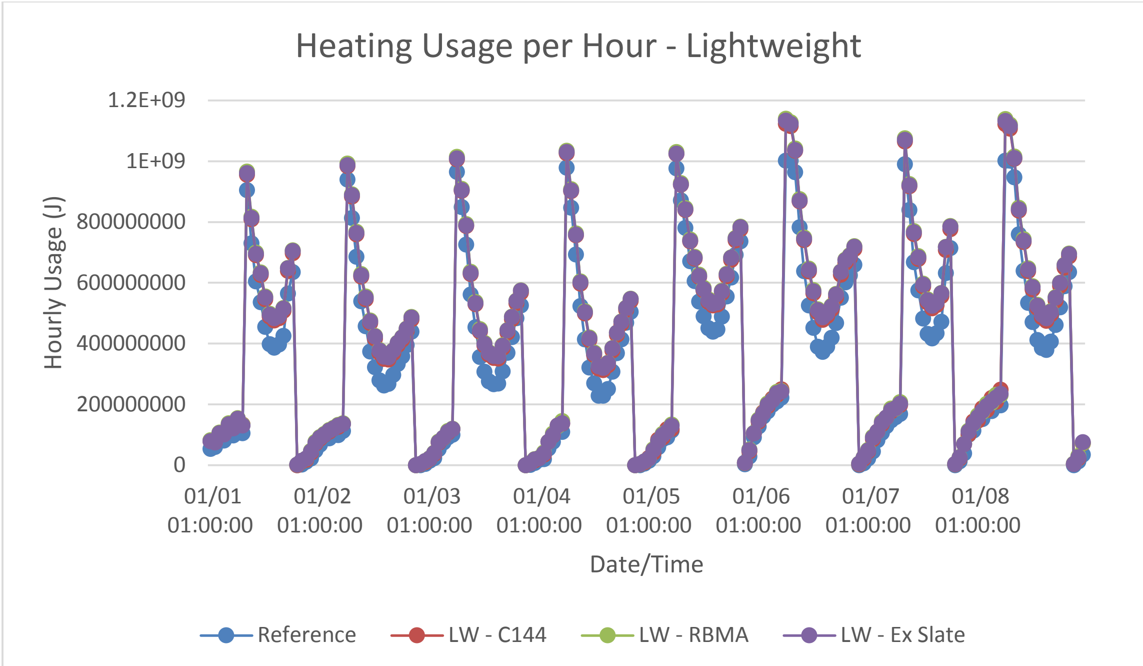

Figure B-5: Boulder, CO lightweight models hourly heating energy consumption in winter

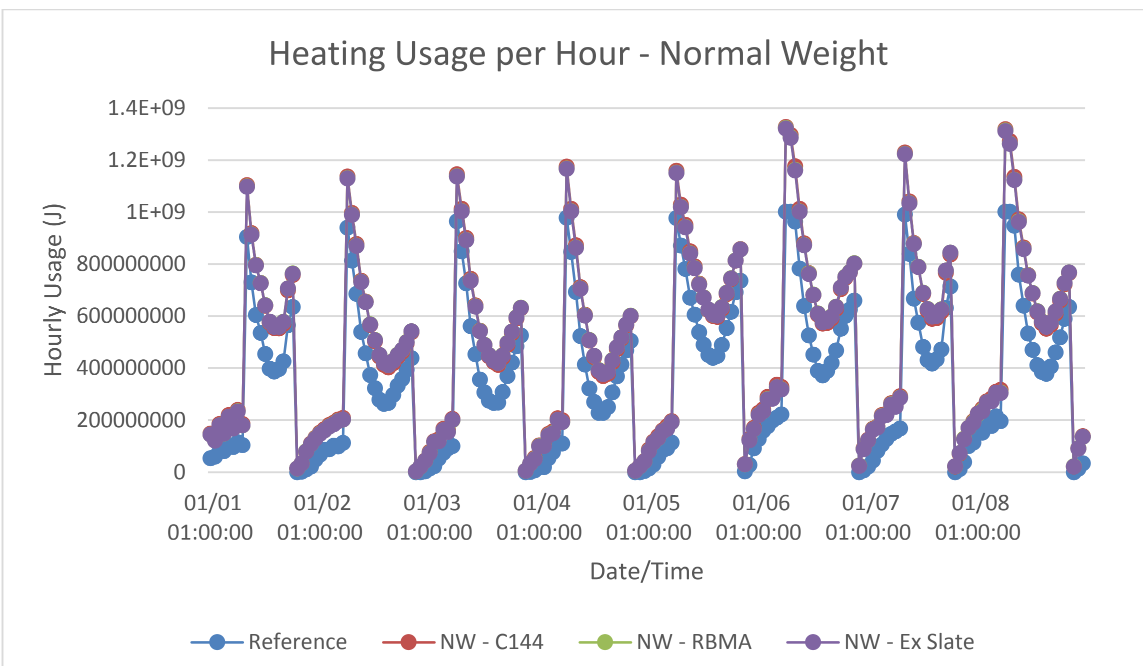

Figure B-6: Boulder, CO normal weight models hourly heating energy consumption in winter

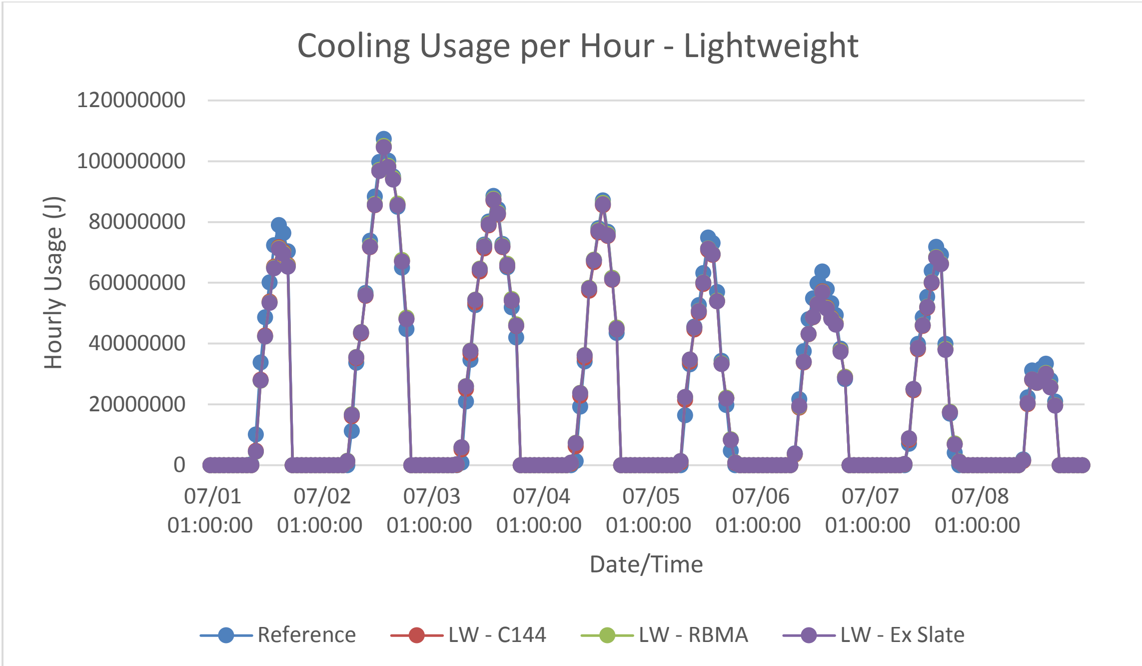

Figure B-7: Boulder, CO lightweight models hourly cooling energy consumption in summer

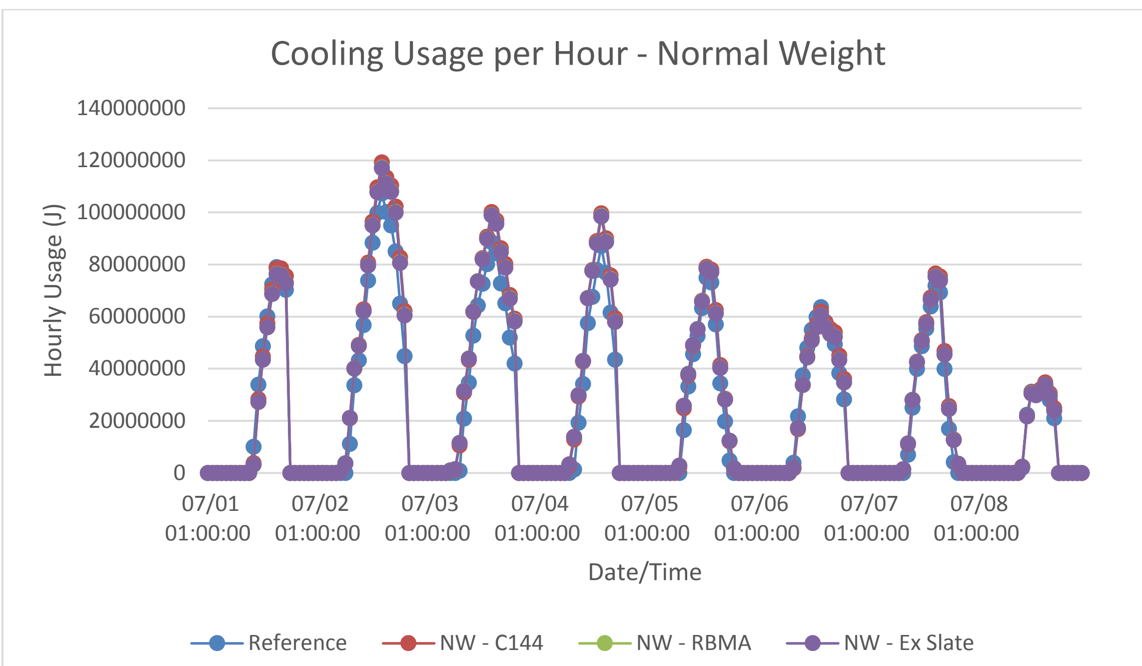

Figure B-8: Boulder, CO normal weight models hourly cooling energy consumption in summer

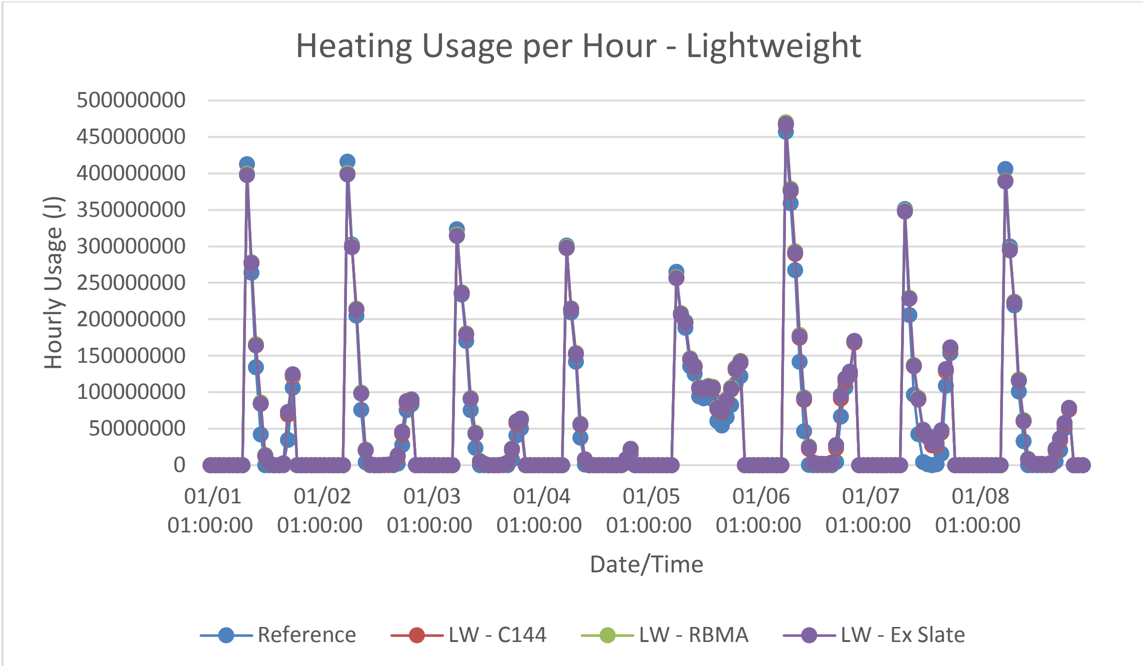

Figure B-9: Los Angeles, CA lightweight models hourly heating energy consumption in winter

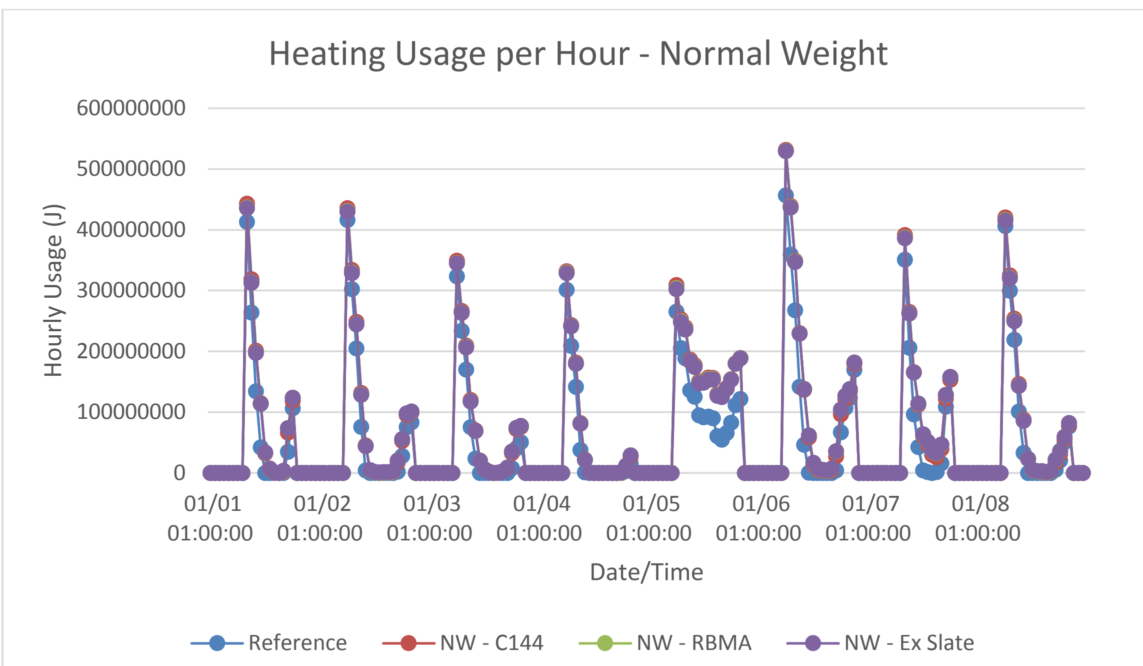

Figure B-10: Los Angeles, CA normal weight models hourly heating energy consumption in winter

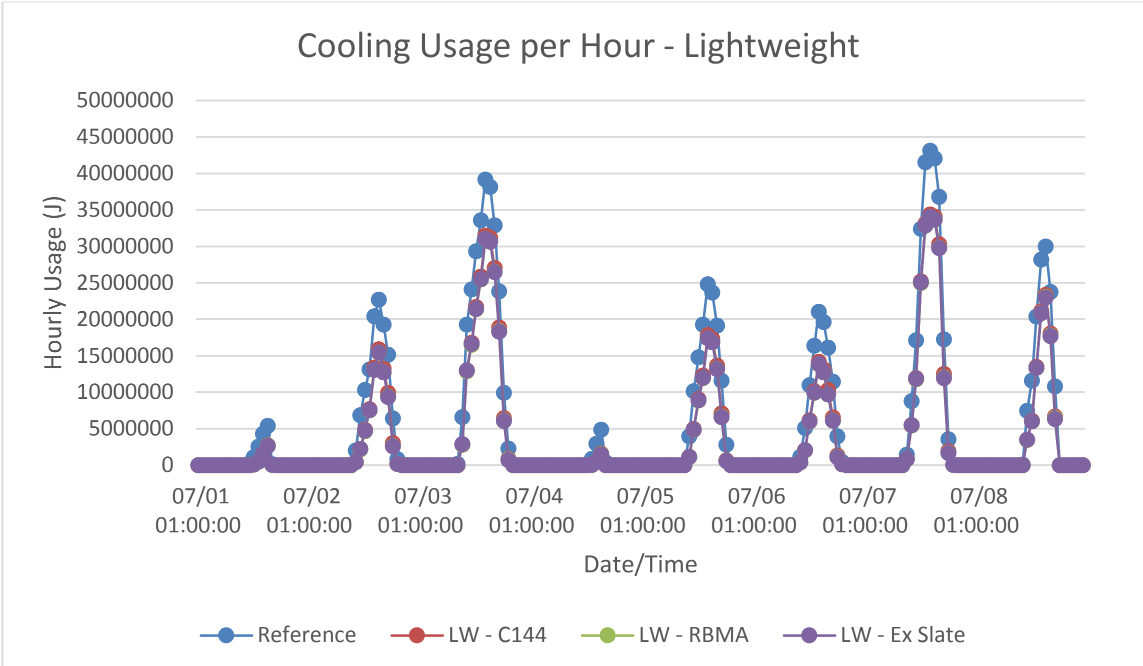

Figure B-11: Los Angeles, CA lightweight models hourly cooling energy consumption in summer

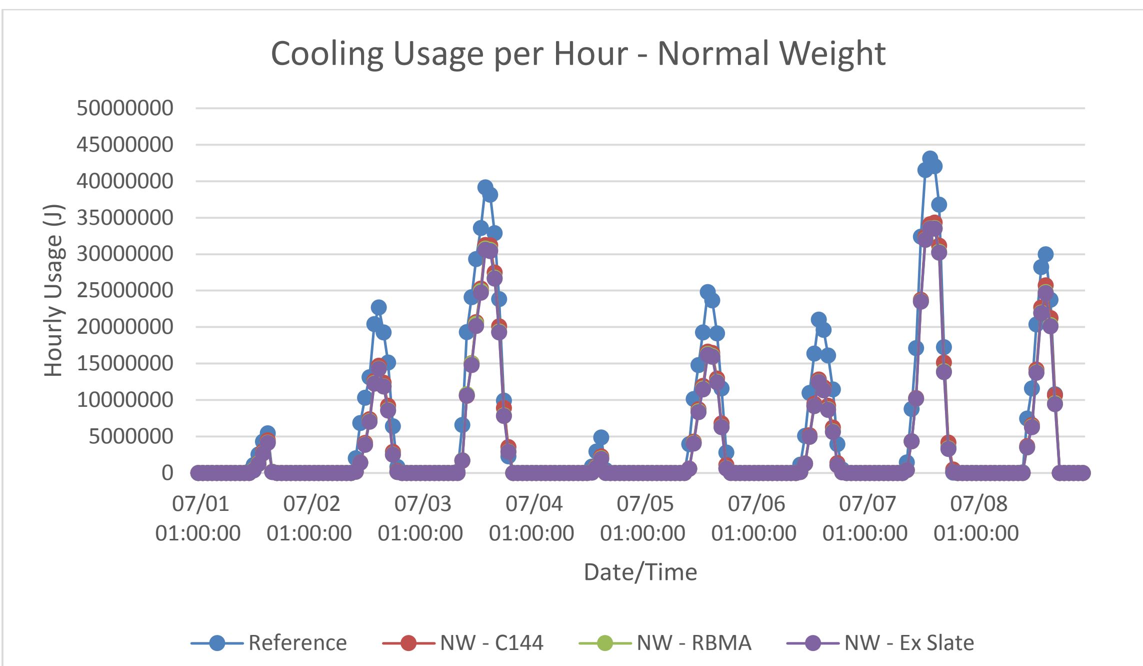

Figure B-12: Los Angeles, CA normal weight models hourly cooling energy consumption in summer

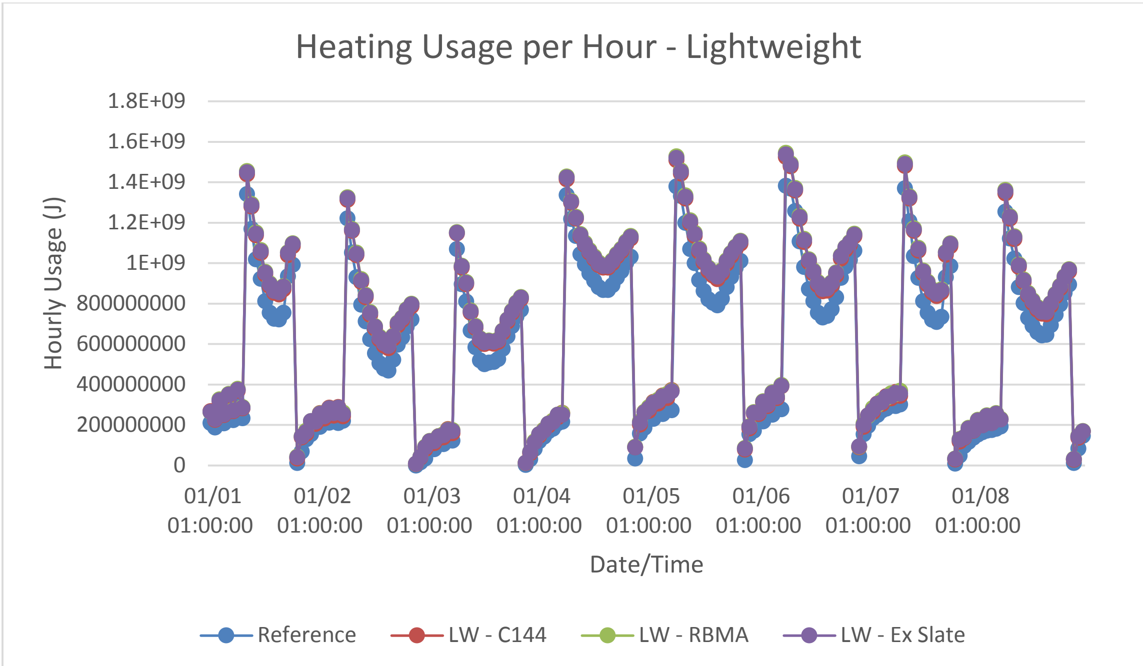

Figure B-13: Minneapolis, MN lightweight models hourly heating energy consumption in winter

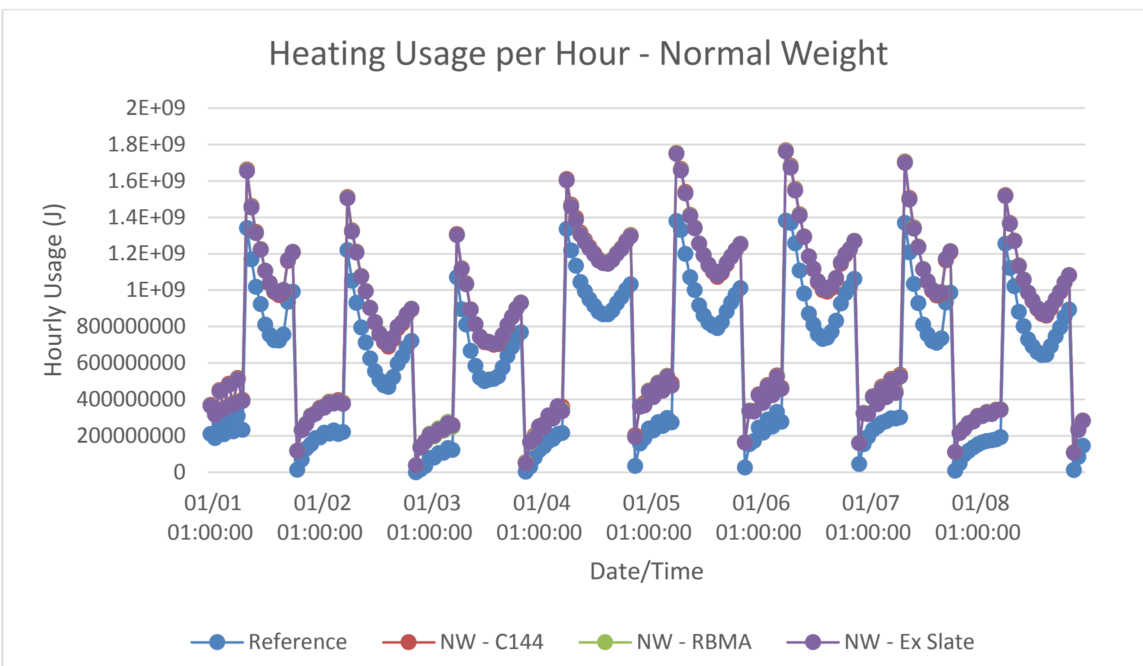

Figure B-14: Minneapolis, MN normal weight models hourly heating energy consumption in winter

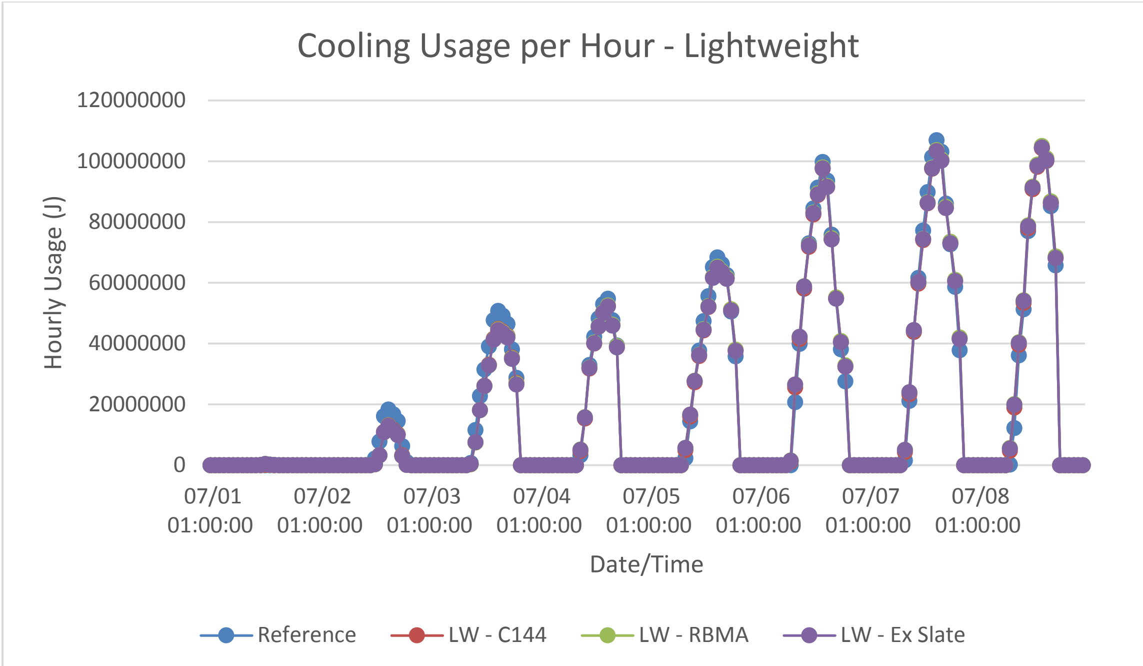

Figure B-14: Minneapolis, MN lightweight models hourly cooling energy consumption in summer

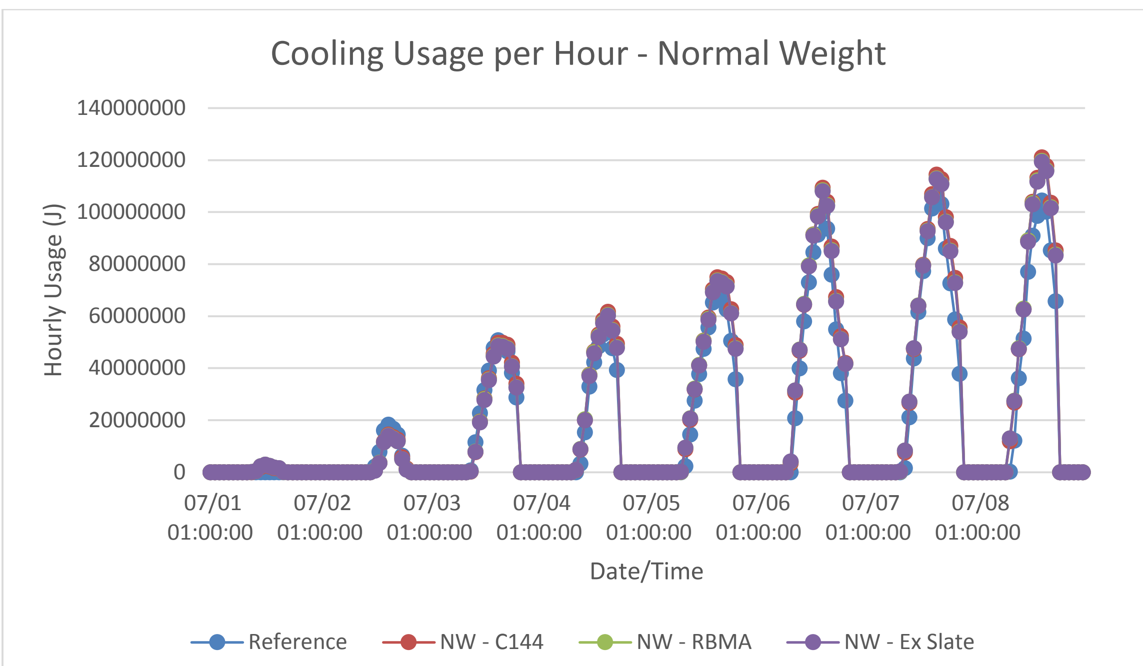

Figure B-14: Minneapolis, MN normal weight models hourly cooling energy consumption in summer

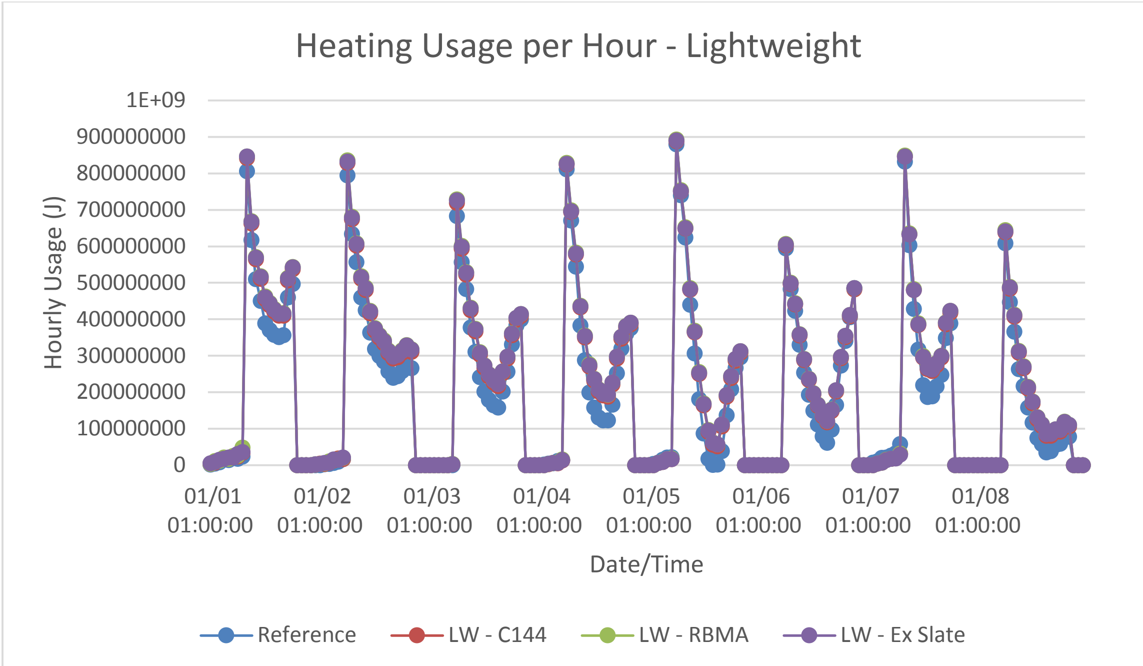

Figure B-15: Baltimore, MD lightweight models hourly heating energy consumption in winter

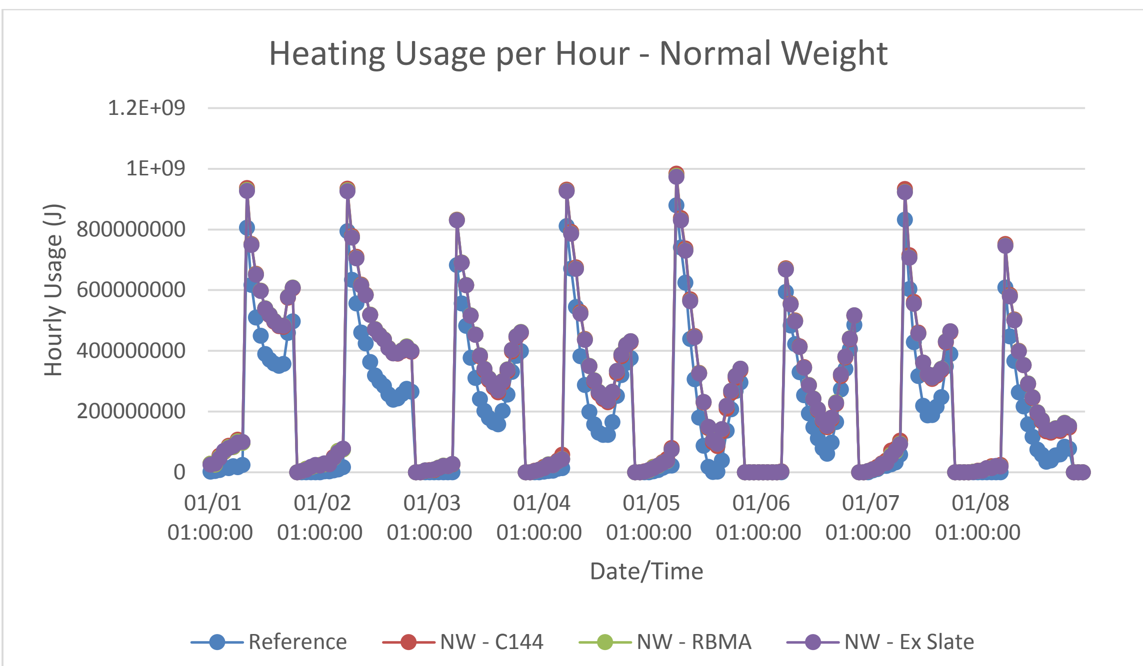

Figure B-16: Baltimore, MD normal weight models hourly heating energy consumption in winter

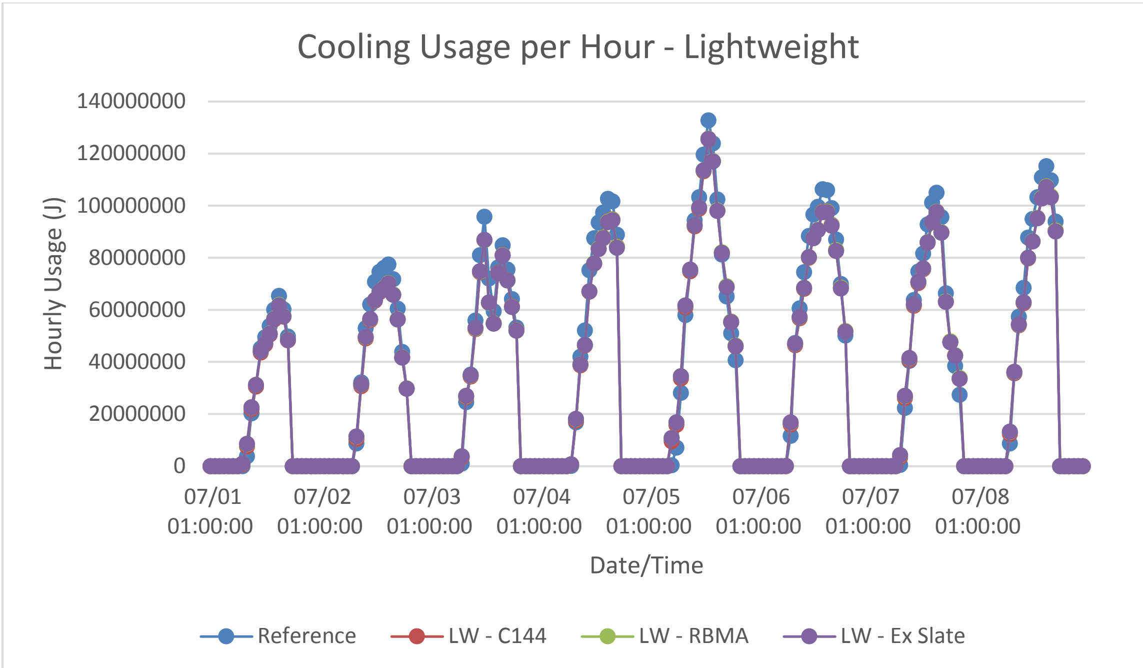

Figure B-17: Baltimore, MD lightweight models hourly cooling energy consumption in summer

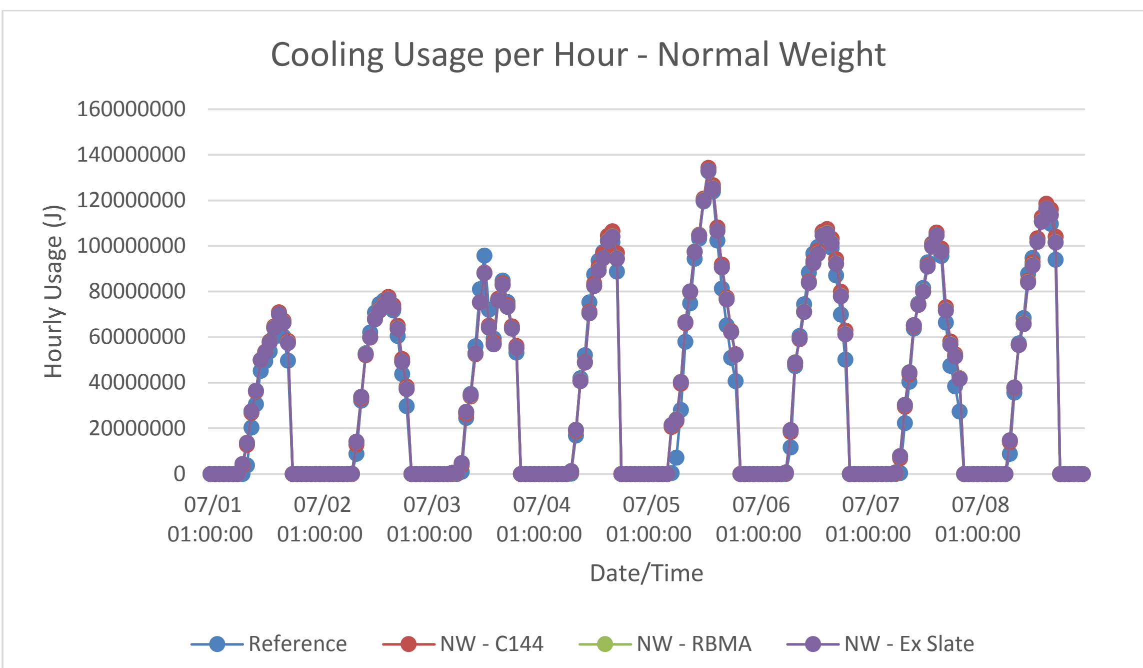

Figure B-18: Baltimore, MD normal weight models hourly cooling energy consumption in summer

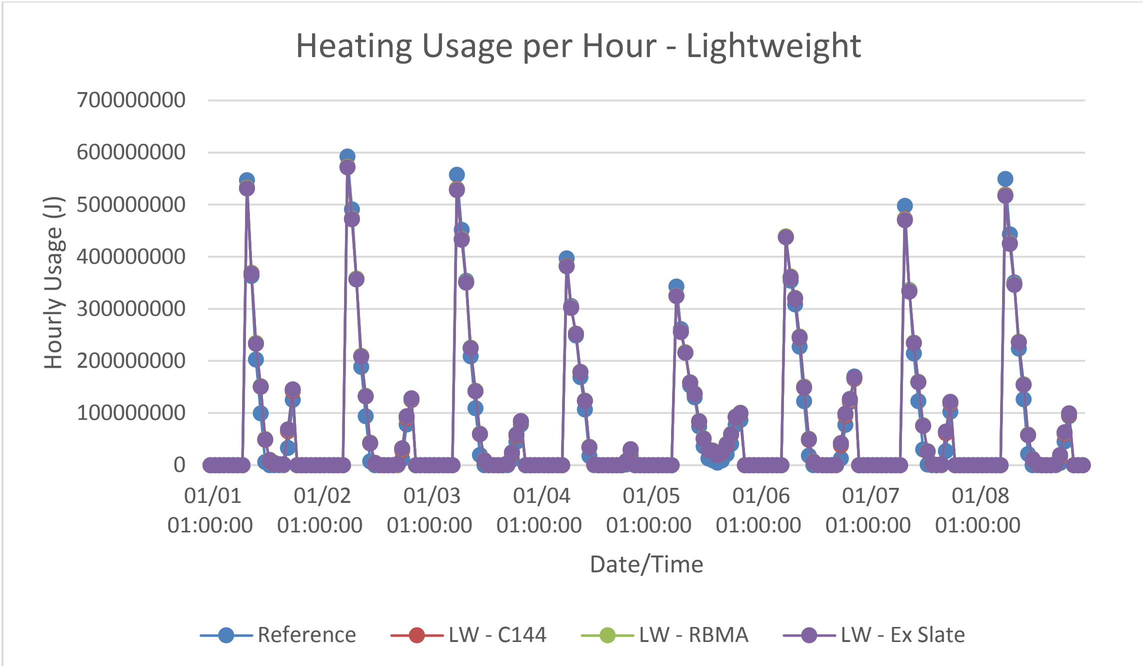

Figure B-19: Phoenix, AZ lightweight models hourly heating energy consumption in winter

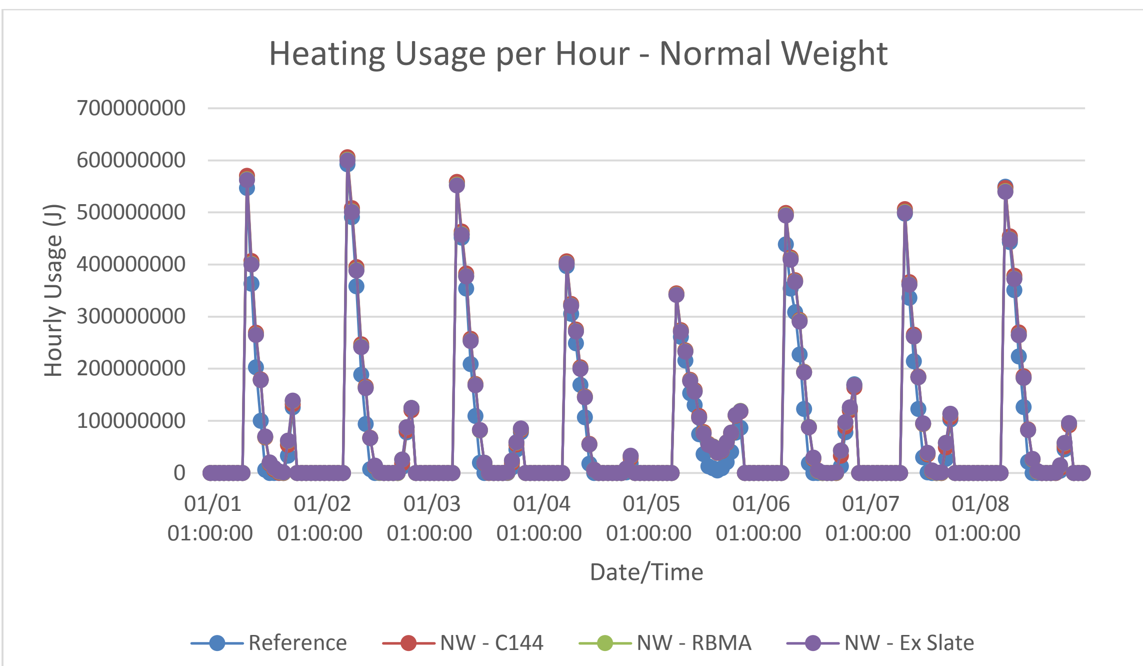

Figure B-20: Phoenix, AZ normal weight models hourly heating energy consumption in winter

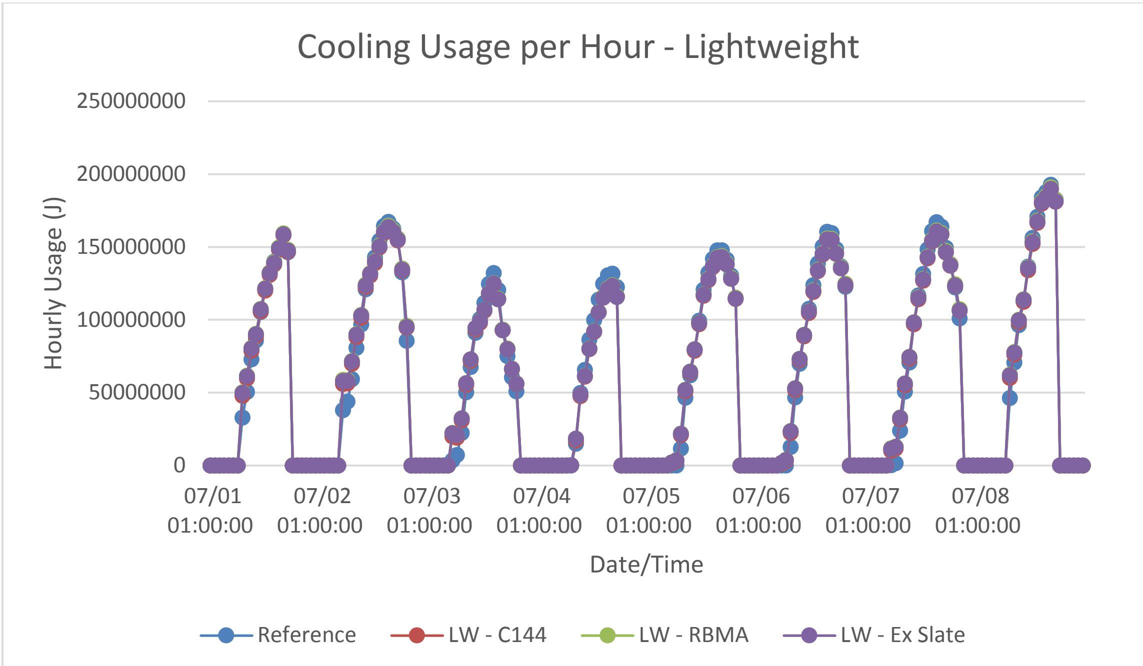

Figure B-21: Phoenix, AZ lightweight models hourly cooling energy consumption in summer

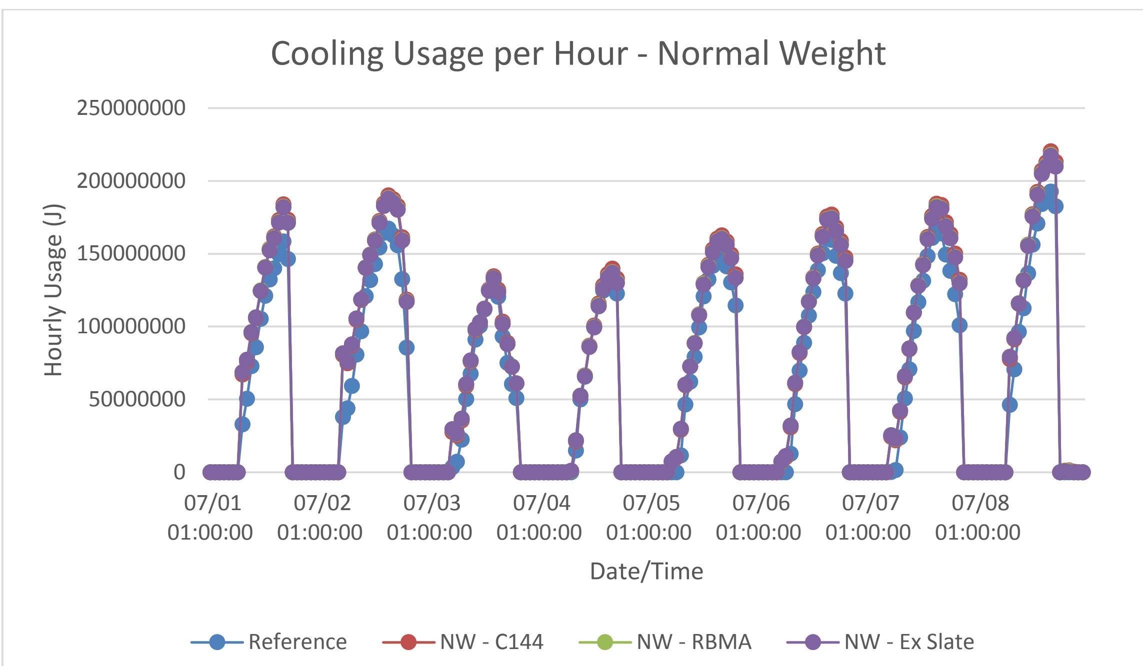

Figure B-22: Phoenix, AZ normal weight models hourly cooling energy consumption in summer

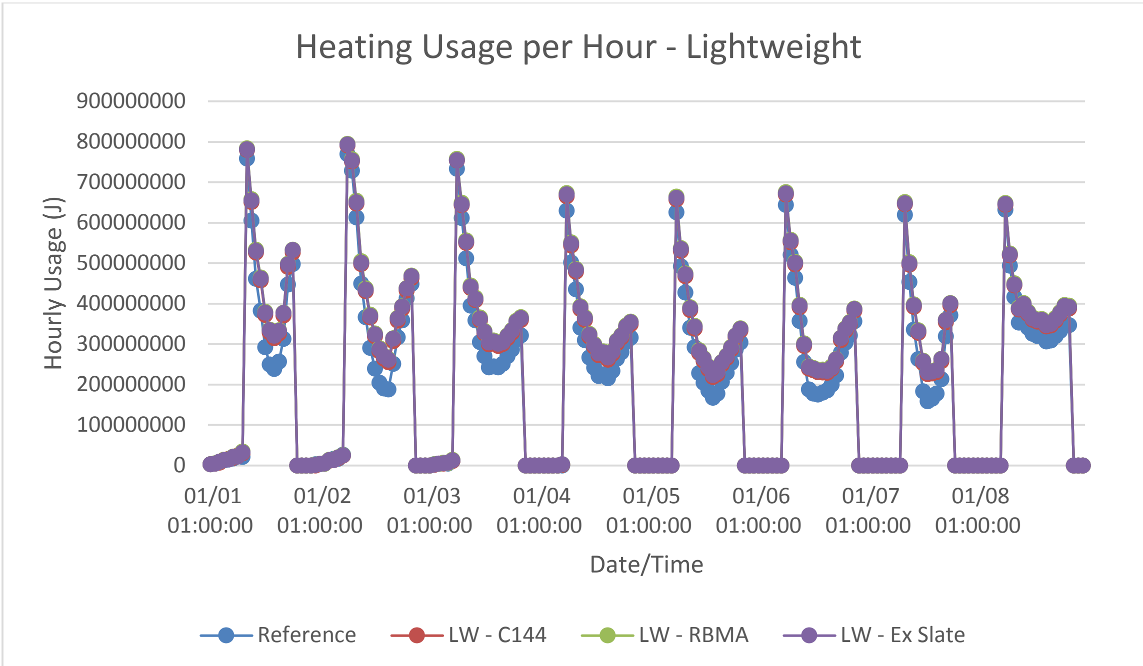

Figure B-23: Seattle, WA lightweight models hourly heating energy consumption in winter

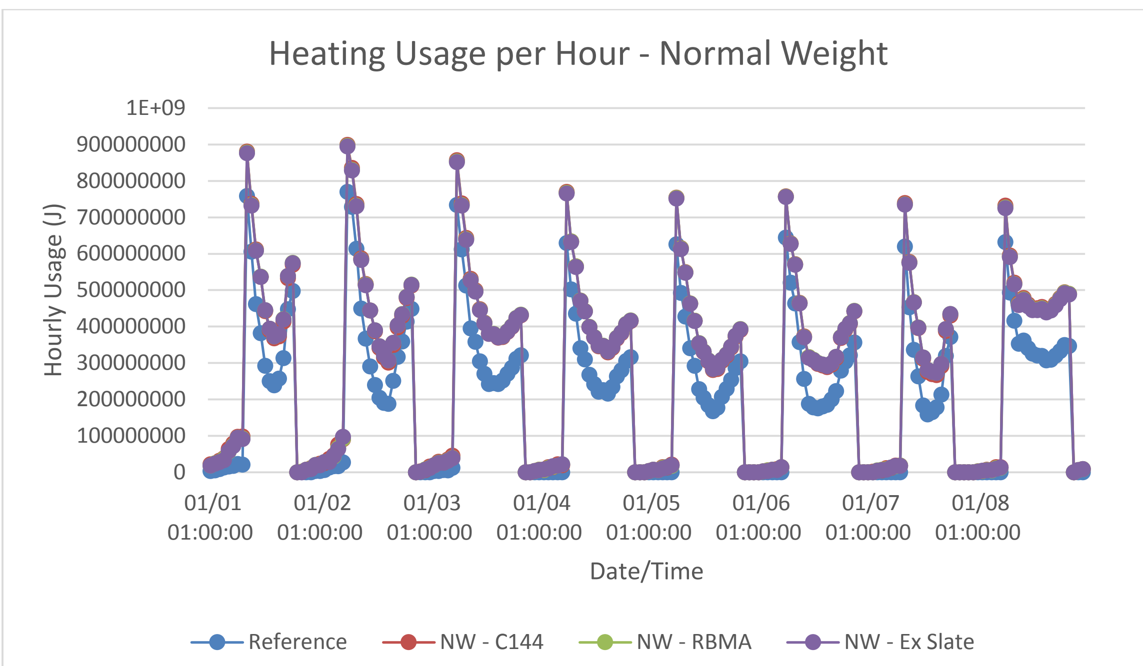

Figure B-24: Seattle, WA normal weight models hourly heating energy consumption in winter

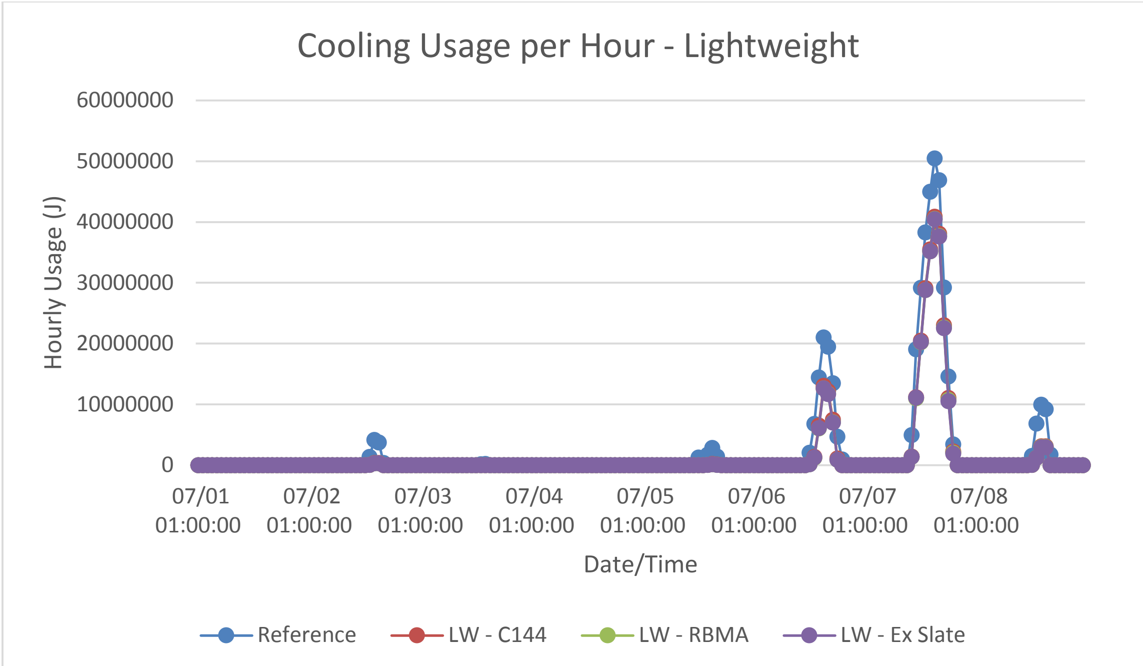

Figure B-25: Seattle, WA lightweight models hourly cooling energy consumption in summer

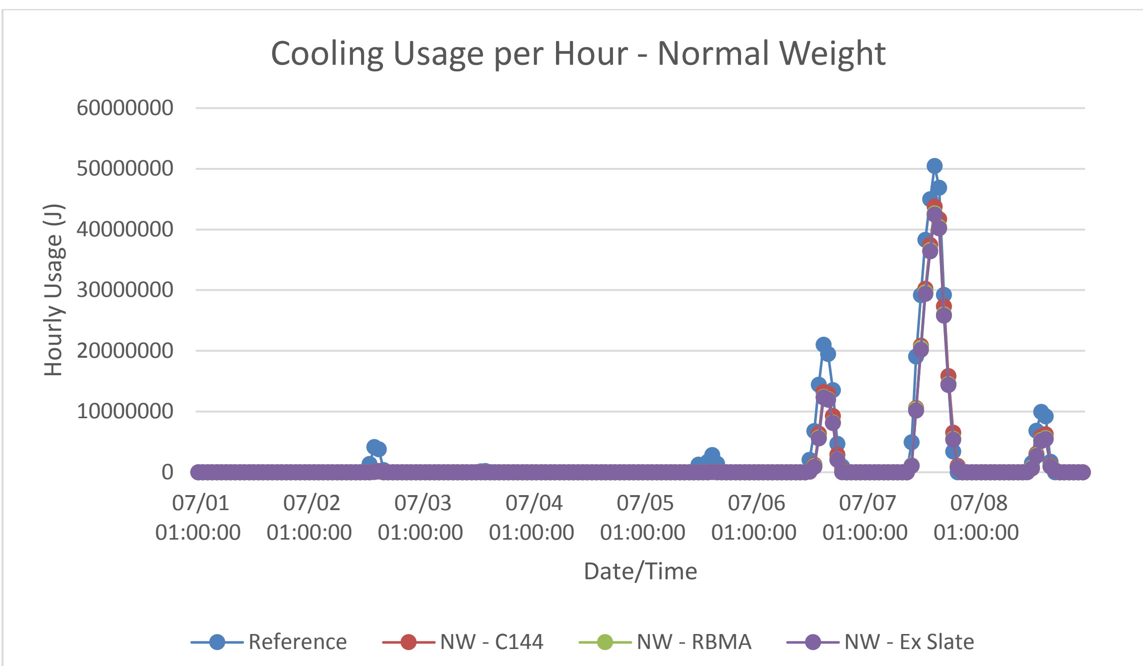

Figure B-26: Seattle, WA normal weight models hourly cooling energy consumption in summer

APPENDIX C: RAW ENERGYPLUS DATA

For each EnergyPlus model, there were a number of output files containing pertinent data points used to generate the results in this report. Due to the large amount of information, it is available upon request by contacting Morgan Laney at mlaney10@uncc.edu.