Effects of concrete thermal mass on energy efficiency

by

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Abstract

Architectural engineers are committed to designing safe, efficient, and innovative structures for the community. The goal is to produce the best design; this includes creating an efficient, cost-effective, and sustainable design. To achieve this goal, new and relevant techniques must continue to be discovered to keep up with a growing industry. A major factor moving forward in the industry is sustainability, by reducing carbon emissions. Carbon emissions profoundly affect the environment, primarily through climate change and global warming. Solutions to decrease carbon emissions can be achieved by reducing embodied carbon (selecting appropriate construction materials) and operational carbon (maximizing energy efficiency). This report will focus on the thermal mass effects of concrete and how these thermal properties can be used to reduce carbon emissions. Thermal mass refers to the ability of a material to absorb and store heat energy. Concrete's thermal mass properties can significantly impact the performance and sustainability of a building by influencing both energy consumption and regulating indoor air conditions by slowing down heat transfer. A case study investigated the effects of increased thermal mass in concrete walls versus the thermal and energy performance of buildings in different geographical locations throughout the United States. The results of several different concrete wall thicknesses are compared by carbon emission output, energy demand, and overall cost. The carbon emission impacts will be compared through embodied carbon from producing concrete and operational carbon energy due to HVAC demands. The findings will provide considerations for integrating high thermal mass into sustainable building design and offer insight for architects and engineers. The results indicate that thermal mass can positively affect a building's energy efficiency and carbon footprint for cold, temperate, and hot climate regions.

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Chapter 1: Introduction

Structural engineers are committed to designing safe, efficient, and state-of-the-art structures for the community. The goal is to produce the best design; this includes creating an efficient and sustainable design. To achieve this goal, new and relevant techniques must continue to be discovered to keep up with the industry's growth. The primary factor moving forward in the industry is reducing carbon emissions as environmental issues such as global warming continue to rise. Global warming is a growing problem, and carbon emissions are the main contributor to this issue (Kabir et al., 2023). Carbon emissions profoundly affect the environment, primarily through climate change. Carbon dioxide is a greenhouse gas that traps heat in the Earth’s atmosphere. Earth needs greenhouse gases to keep the average surface temperature above freezing. However, by adding additional carbon dioxide to the atmosphere, society is supercharging greenhouse gases, causing global temperatures to rise. The rising temperatures are causing altered precipitation patterns and more frequent and severe weather events such as hurricanes, heatwaves, and droughts. These changes cause disruptions to ecosystems and biodiversity (Kabir et al., 2023). Overall, addressing the issue of carbon emissions is crucial for alleviating the impacts of climate change and protecting the environment.

The building industry, residential and commercial, makes up roughly 40% of the world's carbon emissions (Karlsson et al., 2020). Sustainability within buildings and materials has become a priority as the industry seeks to minimize its environmental impact. According to the World Commission on Environment and Development of the United Nations, sustainability means meeting the needs of the present without compromising the ability of future generations to meet their own needs (Naik, 2008). Goals are being set for net-zero or near-zero energy buildings to reach climate neutrality. Evidence from research shows it is possible to achieve net-zero in most building types and climates at reasonable costs. Maximizing energy efficiency has become a top priority within design and construction. In recent years, 19 countries have committed to climate neutrality to align with emission scenarios outlined by the Intergovernmental Panel on Climate Change (Huang & Zhai, 2021). This means being compatible with the Paris Agreement. The Paris Agreement is a statement that limits the global temperature rise to a maximum of 36 degrees Fahrenheit a year (Ürge-Vorsatz et al., 2020). Projects must limit their carbon footprints to keep the temperature from rising. Heating and cooling are prominent energy use areas that can significantly reduce energy consumption and carbon emissions.

Major Causes of Carbon Emissions

- Energy Consumption: Buildings consume a large amount of energy, and most of this energy is made from fossil fuels such as coal, oil, and natural gas. The energy is used for heating, cooling, lighting, and operating the building systems, resulting in significant carbon emissions. In total, 8% of the global energy-related and process-related CO2 emissions resulted from using fossil fuels in buildings, with another 19% from the generation of electricity used in buildings (Ürge-Vorsatz et al., 2020). The structural material used for a building has a large capacity to impact heat flow and energy efficiency. Insulation and material thermal mass can decrease energy needs by minimizing load demands.
- Materials and Construction Process: The production of building materials, such as concrete, steel, and glass, requires significant energy and generates substantial carbon

emissions. Studies have reported that 9-10% of carbon emissions in the building industry are related to cement and concrete production, transportation, and use (Griffiths et al., 2023). Efficient engineering design can impact how these materials are used correctly to maximize efficiency, durability, and longevity.

- Waste generation: The demolition of buildings at the end of their life contributes heavily to their embodied carbon. Significant waste is created over a building's lifetime, and carbon emissions are produced through transportation, disposal, and decomposition.

Decarbonization is the reduction or elimination of carbon dioxide emissions from manufacturing or energy production processes. A building is broken down into embodied carbon and operational carbon. For structural systems, most emissions come from embodied carbon. Embodied carbon refers to the greenhouse gases arising from the manufacturing, transporting, installation, and disposal of building materials. The building materials of a structure can greatly impact carbon emissions. The operational carbon is associated with the heating and cooling needs of a building and all operating systems. Engineers worldwide are incorporating energy-efficient measures at various stages of the design. Renewable energy sources such as solar, wind, geothermal, or hydroelectric reduce carbon emissions.

Within the materials and construction process, concrete is one of the most widely used construction materials in the world due to its many advantages in terms of durability and strength. However, it contributes massive quantities of carbon emissions through energy-intensive production. With concrete's dense composition and material properties, it has a very high thermal mass. Thermal mass refers to the ability of a material to absorb, store, and release heat energy. This attribute can have a strong influence on the heating and cooling needs of a building. Materials with thermal mass will slow heat transfer from interior and exterior spaces, creating a thermal lag that shifts energy demands to off-peak periods where there will be less stress on the HVAC system and lower utility rates. The thermal behavior of a material is a function of its density, specific heat capacity, and thermal conductivity. The optimal combination of these three properties is the key to the most thermally efficient design. This report aims to evaluate concrete's thermal mass efficiency in improving buildings' thermal performance to achieve human thermal comfort with less energy and carbon emissions, primarily through its thermal mass abilities. A case study investigates the effects of increased thermal mass in concrete walls versus the thermal and energy performance savings of buildings in different geographical locations throughout the United States. This is done by comparing a structure's carbon and energy outputs using various concrete wall types. Increasing the thickness of the concrete and adding insulation will add more heat storage and decrease thermal conductivity, increasing the structure's thermal mass. Increased material production and construction will increase costs and the embodied carbon of a project upfront. However, this increased mass will reduce energy consumption, increasing cost savings throughout the life of a structure. A higher initial investment with greater long-term benefits regarding energy demand and utility costs: using more thermal mass in a design will decrease energy demands and carbon emissions throughout the building's lifecycle.

Chapter 2: Concrete Sustainability

Concrete sustainability consists of strategies and practices to reduce the environmental impact of concrete production, construction, and disposal. Concrete is one of the world's most prominent construction materials, widely used in buildings, bridges, roads, and many other forms of infrastructure. Concrete is desirable due to its strength, durability, relatively low cost, and usability. This material comprises three main ingredients: a cementitious material, potable water, and aggregate. Depending on the design, various admixtures are added for air entrainment and water reduction. The cementitious material is a finely ground powder made from limestone, clay, or other materials. Cement accounts for approximately 10-15% of the total weight of a mix (Griffiths et al., 2023) and acts as the primary binding agent in the concrete, forming a paste when mixed with water that binds together the aggregates. Portland cement is the most common cementitious material used worldwide (Purnell, 2013) because of its low cost, easy availability, and quality workability. Cement production is both resource and energy-intensive, which causes it to be a significant contributor to carbon emissions. However, it continues to be the most widely used building material, so the building industry is taking initiatives to prompt the sustainable design of concrete through carbon footprint reduction, conserving natural resources, and minimizing waste throughout the concrete's lifecycle.

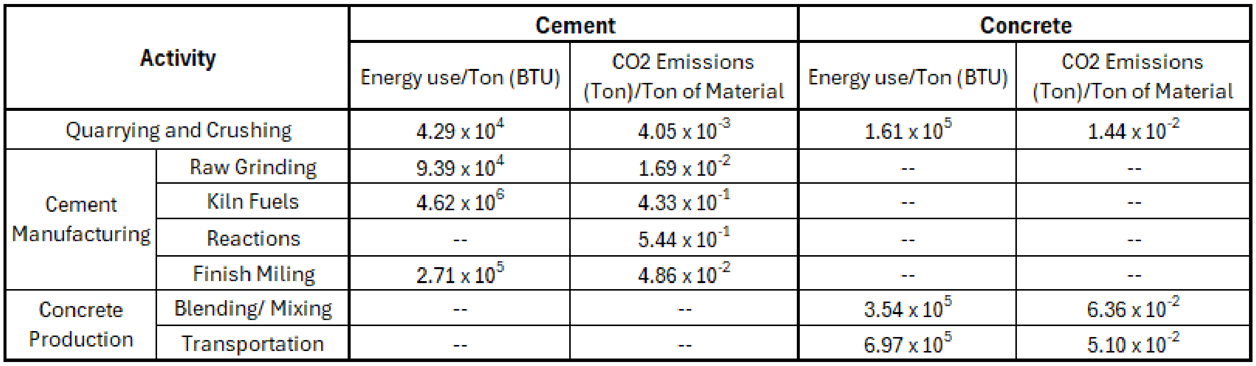
There are many contributors to concrete's environmental impacts, mainly cement production and construction. Cement and concrete production, transport, use, and demolition account for roughly 9-10% of global energy-related CO2 emissions, including carbonate decomposition, fuel combustion, and electricity use (Griffiths et al., 2023). Cement production alone accounts for 77% of that 9-10% total, making it the most significant point of sustainability focus. Within the building industry specifically, concrete accounts for 6% of the carbon emissions. Concrete sustainability can be achieved by identifying the leading causes and creating solutions to reduce the carbon footprint and increase energy efficiency.

Causes of Carbon Emissions in Concrete

- Production of Cement/Concrete: Portland cement is not environmentally friendly because its manufacturing process creates a large quantity of greenhouse gas emissions. Sources of CO2 and GHG emissions in the production of Portland cement are as follows (Naik, 2008):
    - 50-55% from calcination of limestone
    - 40-50% from fuel combustion
    - 5-10% from the use of electric power

  Production releases significant amounts of CO2 mainly through clinker production, which is the heating of limestone and clay. The calcination process occurs in the kiln, producing nearly 0.55 kg CO2 per kg of cement (Sizirici et al., 2021). Like a large oven, a kiln is a thermally insulated chamber that evaporates the water from the raw material and then calcinates the limestone. The limestone is heated in a kiln until it is converted into lime and carbon dioxide. The primary fuel source for these operations comes from burning fossil fuels, which are more sources of CO2. These combined sources of emissions alone make cement production one of the largest industrial sources of CO2 globally. The production of one ton of Portland cement produces roughly one ton of CO2 and other greenhouse gases (Sizirici et al., 2021). These emissions are just from kiln fuels and reactions; the entire concrete production process contributes to the total emissions.

Ultimately, one cubic yard of traditional concrete produces about 400 pounds of carbon dioxide (Structural Engineering Institute). To put this into perspective, a typical passenger vehicle emits roughly 20 pounds of CO2 per gallon of gas burned (US EPA, 2016). The energy consumption on-site and CO2 emissions from the production of cement/concrete annually are listed in Table 1 (Sizirici et al., 2021).



Activity		Cement		Concrete	
		Energy use/Ton (BTU)	CO2 Emissions (Ton)/Ton of Material	Energy use/Ton (BTU)	CO2 Emissions (Ton)/Ton of Material
Quarrying and Crushing		4.29×10^{4}	4.05×10^{-3}	1.61×10^{5}	1.44×10^{-2}
Cement Manufacturing	Raw Grinding	9.39×10^{4}	1.69×10^{-2}	--	--
	Kiln Fuels	4.62×10^{6}	4.33×10^{-1}	--	--
	Reactions	--	5.44×10^{-1}	--	--
	Finish Miling	2.71×10^{5}	4.86×10^{-2}	--	--
Concrete Production	Blending/ Mixing	--	--	3.54×10^{5}	6.36×10^{-2}
	Transportation	--	--	6.97×10^{5}	5.10×10^{-2}

Table 1: Energy Use and CO2 Emissions from Cement/Concrete Production Annually

- Construction Process: Concrete is created by mixing cement, aggregates, and water and then must be cured for some time to develop strength. During the curing process, the cement reacts with the water to form a solid material. The curing process takes place immediately after the concrete is placed and finished. It maintains satisfactory temperature and moisture conditions long enough for hydration to develop the desired concrete properties. The produced reaction, called hydration, does not directly release carbon dioxide. However, a lot of energy is required for this process to occur, which will mean more burning of fossil fuels. The same goes for other construction processes, such as the aggregate transportation to the cement plant and the cement transportation to the job site. CO2 emissions from transportation and on-site construction account for 2.4% and 4.2% of the total emissions (Seo et al., 2016). The same goes for the emissions produced from vehicle transportation and machinery during the demolition phase. Concrete itself does not emit carbon once it is cured and in place. The emissions come from the energy used in production, construction, and demolition.

Existing Solutions

Concrete is a building material that is strong and durable and there are low-carbon technologies and practices being implemented to reduce concrete’s impact on the environment. The goal is to reduce carbon emissions without compromising the favorable attributes of concrete. Practices in sustainable concrete not only offer economic advantages but also contribute to environmental preservation. Concrete can be more sustainable and cost-efficient by minimizing energy use, obtaining materials from local sources, and reducing waste.

- Resource Efficiency: The production of concrete requires many natural resources. As stated earlier, one ton of Portland cement produces one ton of carbon dioxide; likewise, one ton of Portland cement uses 1.6 tons of raw materials (Naik, 2008). Portland cement reduces the supply of good-quality limestone, a dependable building material. Solutions to reduce carbon emissions and resource depletion include using alternative, low-carbon cementitious materials such as fly ash, slag, and calcined clays instead of Portland cement or recycling aggregates and water. These substitute materials can contribute to the future reduction of concrete embodied carbon and improve the long-term physical properties of concrete. Most innovative concrete mixes use these materials to partially replace the cement. The advantages of blended cement mixtures include increased production capacity, lower greenhouse gas emissions, and reduced fuel consumption. These materials are the byproduct of burning fossil fuels such as coal. Therefore, they are more of a recycled material and do not purely reduce carbon emissions, the fossil fuels will still be burned. With the increased use in renewable energy systems there are not as many fossil fuels burning which is resulting in a shortage of these byproducts such as fly ash. These materials eventually will not be readily available in the United States and will come with added costs and environmental impacts from tariffs on imports and the transportation needed. Plastic aggregate is another growing solution that replaces some aggregates with recycled plastics. This will help reduce plastic waste and alleviate natural resource scarcity.

- Carbon Capture and Storage: Another solution is to utilize carbon capture and storage (CCS) technologies, which will capture carbon dioxide emissions from cement plants as the cement is produced. This is accomplished by containing and compressing the emissions from the plant, piping it away, and storing it deep underground. It will be trapped there beneath the impermeable layers of rock. Carbon capture systems do not capture 100% of emissions, but most are designed to capture 90% (Lebling et al., 2023). Carbon capture storage is a temporary solution to holding off CO2 emissions because the carbon is held deep underground where it cannot harm the environment. However, it is still there, so this is not a solution to reaching net-zero emissions. CO2 could be trapped for millions of years, but well-selected underground storage areas are likely to retain over 99 percent of the injected CO2 over 1000 years (Raza et al., 2019). CCS technology is still young and will require more studies to ensure that its capture and storage can effectively reduce or remove environmental carbon emissions.
- Durability and Longevity: Designing and constructing durable concrete structures can extend the service life, reducing the need for replacements and repairs. Larger, more

energy-efficient designs in the beginning impact the building's life. These larger designs will come with higher upfront costs and more embodied carbon, but these costs and carbon emissions can be reduced through an extended life and quality design. Durable structures with longer life cycles will reduce the need for more demolition and new construction, significantly lowering carbon emissions. A central component of thicker concrete construction is increased thermal mass, which creates energy efficiency.

The main goal is to reduce the carbon footprint. solutions to reduce carbon footprint can be achieved by combining embodied carbon (selecting appropriate construction materials) and operational carbon (maximizing energy efficiency). Concrete has good thermal properties and high thermal mass, allowing it to absorb and slow heat transfer. Concrete’s high thermal mass can decrease energy demand and lower operational carbon emissions by maximizing a structure's thermal efficiency.

Carbon Footprint

Carbon footprint measures the amount of carbon dioxide and other greenhouse gases emitted by a particular person, group, or thing. A building's carbon footprint is the total amount of greenhouse gases generated throughout its life, from construction to disposal. It encompasses emissions from materials, energy used in construction, and operational energy. The construction industry contributes one of the largest carbon footprints and is listed among the most prominent global consumers of resources.

A building or structure is broken down into embodied carbon and operational carbon. The embodied carbon of a structure refers to carbon impacts associated with the construction process and material production and transportation. The structure and façade account for 80% of a building's embodied carbon (Cortese, 2020), with concrete and steel having the highest embodied carbon content. Solutions to reducing embodied carbon include using low-carbon materials such as recycled steel and mass timber, reducing total materials used in a design, and repurposing used materials as much as possible. Operational carbon is associated with building occupancy and includes the emissions it takes to operate the building, such as HVAC systems. This includes the energy used for a building's heating, cooling, and electricity demands. Operational carbon is a day-to-day measurement that engineers can considerably impact. Reducing operational carbon means improving energy efficiency and using renewable energy sources.

The goal is to create net-zero carbon buildings by reducing all operational and embodied emissions. Net-zero carbon is a term that refers to the reduction of greenhouse gas emissions generated from resource consumption to as close to zero as possible. This means any greenhouse gases emitted into the atmosphere are balanced by the removal of greenhouse gases from the atmosphere. The same goes for energy; net-zero energy means consuming no more energy than is produced from renewable sources annually. SE 2050 (Structural Engineers 2050) is a commitment program by SEI (Structural Engineering Institute) and ASCE (American Society of Civil Engineers) for structural engineers and firms to establish carbon benchmarks and reduction goals to achieve net-zero embodied carbon in buildings by the year 2050. Their strategies include planning for a net-zero building sector, implementing more sustainable design, and sharing knowledge so everyone can create a more sustainable industry.

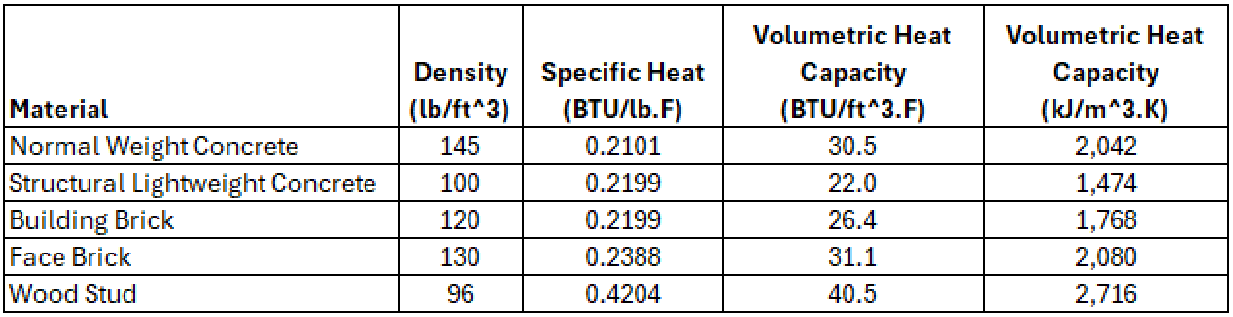
With a growing concern about reducing carbon emissions, looking at buildings from a lifecycle carbon standpoint or carbon footprint is essential. Measuring the carbon footprint will allow the industry to identify the most emission-intensive materials and systems, resulting in finding solutions to reduce emissions. To deliver net-zero carbon emissions, engineers must reduce the embodied carbon implied by designs and identify means for offsetting the balance of carbon impacts through operational carbon content. Applying sustainable practices with alternative materials and techniques can reduce up to 90% of CO2 emissions at different stages in the construction industry (Sizirici et al., 2021). Energy efficiency will reduce operational carbon within a building, and from a structural standpoint, the material used for a structure can significantly impact its energy efficiency. Concrete’s high thermal mass properties can create thermal energy efficiency by storing heat and slowing heat transfer. Implementing more thermal mass into a building design will create more energy efficiency.

Chapter 3: Thermal Mass

Thermal mass refers to the ability of a material to absorb, store, and release heat. In terms of building materials, it describes their ability to resist temperature fluctuations. It has a beneficial influence on the temperature regulation and energy efficiency of buildings. The idea is that buildings with higher thermal mass will require less energy for heating and cooling as the stored heat can provide a barrier or buffer against outside temperatures. The effectiveness of a building’s thermal mass depends on design, climate, material properties, and other factors. In warmer climates, thermal mass will help keep interiors cooler by absorbing and dissipating heat slower, while in cooler climates, it can help retain heat. Early civilizations used stone and clay construction to sustain life in very hot climates centuries before air conditioning existed. In today's building industry, buildings constructed of concrete and masonry have the same energy-saving advantage because of their inherent thermal mass. Heat transfer will help regulate indoor temperatures, energy requirements, and occupant comfort. The ideal scenario would be to have thermal mass effectively eliminate the need for air conditioning (heating and cooling) or reduce the demand for energy systems.

Three main building components contribute to the overall thermal mass: The building envelope and structural elements, the air volume, and the building fittings, which consist of furniture and other objects. This report will focus on the thermal mass properties of the envelope and building structure, specifically the concrete structure. The higher the thermal mass of the material, the higher its ability to store heat. Some examples of construction materials with thermal mass properties are listed in Table 2 (Vangeem et al., n.d.). Materials with higher densities are usually known for having higher thermal mass due to more heat storage capacity.

Concrete is known for its high thermal mass because of its density, specific heat capacity, and thermal conductivity, making it a strong choice for moderating temperature fluctuations in structures. Optimizing the best combination of these properties of a material can increase the thermal mass and create the most efficient system for a particular climate. Volumetric heat capacity is a relation between specific heat capacity and density by multiplying the density by the specific heat capacity.



Material	Density (lb/ft^3)	Specific Heat (BTU/lb.F)	Volumetric Heat Capacity (BTU/ft^3.F)	Volumetric Heat Capacity (kJ/m^3.K)
Normal Weight Concrete	145	0.2101	30.5	2,042
Structural Lightweight Concrete	100	0.2199	22.0	1,474
Building Brick	120	0.2199	26.4	1,768
Face Brick	130	0.2388	31.1	2,080
Wood Stud	96	0.4204	40.5	2,716

Table 2: Heat Capacity Properties of Various Building Materials

Other building materials, such as steel and timber, illustrate significant thermal properties. Timber has a low density but a much higher specific heat capacity and low thermal conductivity, making it ideal for energy efficiency. However, it does not contain large amounts of thermal mass. Typically, wood construction does not have large sections. Wood studs do not take up much space, making it challenging to use thermal mass effectively. Steel has high density and one of the lowest thermal conductivity values, making it ideal for high-temperature environments. On the other hand, it has the lowest specific heat capacity and, similar to timber, does not take up much space compared to concrete. Concrete is the best material to use to maximize thermal mass benefits in a structure because of its high density, high specific heat capacity, low thermal conductivity, and large spread-out applications such as floors and walls.

Concrete Thermal Properties

Concrete performs well in sustainable design when compared to other materials. It combines insulation with high thermal mass and low air infiltration to make buildings more energy efficient. The thermal resistance varies depending on the type of concrete, and there are endless combinations of concrete mixes used in projects. The R-value measures the heat resistance a material has to heat flow. The standard R-value of normal-weight concrete is between 0.1 and 0.2 (°F-ft^2-h/Btu) per inch of thickness (Trainor, 2024). The higher the R-value, the more thermal resistance a material has. All types of concrete typically have a low R-value, but thermal mass is not a substitute for insulation. Generally, low-density concrete tends to have a higher R-value than high-density concrete because, in low-density, the heat energy has a more considerable distance to travel between masses. This gives the material less thermal conductivity. Thermal mass and thermal resistance are two different measures. Thermal mass stores and slowly releases heat energy, while insulation and thermal resistance slows heat energy from flowing in or out of a space. Concrete is generally used with insulation to gain the most benefit. For comparison, typical recommendations for R-values for exterior wood frame walls range from R-13 to R-23, depending on the climate (Hung Anh & Pásztory, 2021). Most of the R-value comes from added insulation, but these walls have lower thermal mass. Concrete has desirable thermal mass properties that allow it to store large amounts of heat energy and distribute it slowly. Density, specific heat capacity, and thermal conductivity define a material's thermal mass and resistance. These properties, in combination with insulation, make concrete a strong heat regulator.

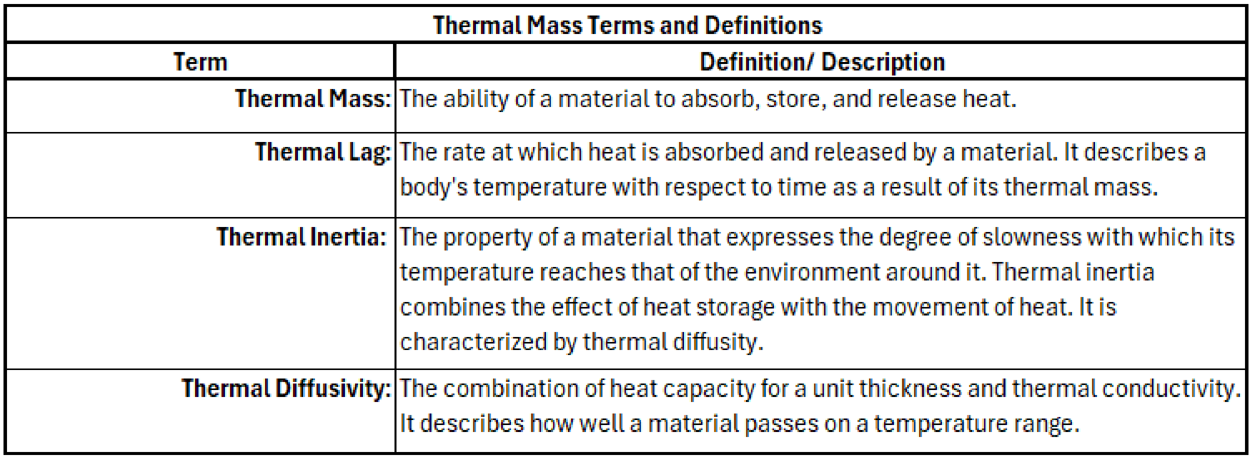
- Density: Concrete contains a high mass per unit volume, which gives it a higher density and allows for more heat storage. The more density, the more storage there is for heat energy particles. The standard density of normal-weight concrete is 140-150 lb./ft^3 (Vangeem et al., n.d.). The density can vary depending on the mix and materials used. The variations affect the concrete's strength, durability, workability, and shrinkage. A higher density generally indicates higher strength and durability, and in the case of thermal properties, there is more thermal storage. Denser concrete has many upsides and raises many construction properties, but it can also have negative impacts. With more density comes more weight, which can cause concerns with larger foundations and members, which also means more cost and a larger carbon footprint.
- Specific Heat Capacity: Specific heat capacity plays a vital role in thermal performance and is the amount of heat energy required to raise the temperature of a given mass by 1 degree Celsius or 34 degrees Fahrenheit (Reilly & Kinnane, 2017). Concrete has a relatively high specific heat capacity, which means it takes a lot of heat to raise the material's temperature, allowing it to absorb and retain a significant amount of heat. Due to the composition of concrete with multiple materials, the specific heat varies depending on the mix. However, the specific heat capacity typically ranges from 0.179 to 0.238 BTU per pound per degree Fahrenheit (Reilly & Kinnane, 2017). This means it takes around 0.238 BTUs of heat energy to raise the temperature of one pound of concrete by one degree Fahrenheit. For comparison, the specific heat value for steel is 0.119 BTU per pound.
- Thermal Conductivity: Thermal conductivity (k-value) is the ability of a material to conduct heat. This allows a material to distribute heat throughout its mass. Ventilation

> and fabric heat loss are two reasons for heat loss in buildings. Ventilation heat loss is the heat transfer through air replacement by HVAC systems such as heating and cooling. The amount of heat lost through walls and roofs directly affects the energy consumption of buildings, known as fabric heat loss. To reduce heat transfer, it is ideal to have a material with low thermal conductivity. Low conductivity means less ability to transfer heat, so it will be slower, which is good for maintaining thermal conditions. Contributing factors to thermal conductivity include moisture content, temperature, type of aggregate, type of cement, and the overall density of the concrete. Concrete’s low thermal conductivity reduces energy consumption through lower heat transfer.

Changing a batch's mix design or specifying a different type or strength can affect the thermal properties of concrete. Lightweight concrete has less thermal conductivity than normal weight due to the aggregates being spread out further. The energy has a further distance to travel between masses. Buildings that use lightweight concrete can reduce 15% of the heating energy needed compared to normal-weight concrete (Asadi et al., 2018). The downside of lightweight concrete compared to normal-weight concrete is that it costs more and requires much more energy to produce lightweight aggregates. The energy needed to produce lightweight coarse aggregate is nearly 30 times greater than that needed to produce normal-weight aggregates because it needs to be produced in a high-heat rotary kiln. This report and case study on concrete will focus on normal-weight concrete wall panels.

Thermal Lag

The solid thermal properties of the material contribute to regulating indoor air temperature. Thermal mass buffers temperature by creating a heat sink within the material, which provides a time lag, called thermal lag, in transferring heat between two areas. Thermal lag describes a body's temperature with respect to time due to its thermal mass. It slows down the heat transfer between the interior and exterior of a building. This delay will lead to fewer temperature spikes in the heating and cooling requirements since the mass slows the response time and moderates indoor temperature fluctuations. This will shift energy demands to off-peak periods, reducing system stress. Table 3 below defines properties describing thermal storage and heat flow through a material.



Thermal Mass Terms and Definitions

Term	Definition/ Description
Thermal Mass:	The ability of a material to absorb, store, and release heat.
Thermal Lag:	The rate at which heat is absorbed and released by a material. It describes a body's temperature with respect to time as a result of its thermal mass.
Thermal Inertia:	The property of a material that expresses the degree of slowness with which its temperature reaches that of the environment around it. Thermal inertia combines the effect of heat storage with the movement of heat. It is characterized by thermal diffusity.
Thermal Diffusivity:	The combination of heat capacity for a unit thickness and thermal conductivity. It describes how well a material passes on a temperature range.

Table 3: Thermal Mass Terms and Definitions

Thermal lag measures the inside surface temperature's response to outdoor temperature fluctuations. This occurs because of the thermal moment of inertia of the material, which measures how well a material can absorb and release heat. This process is illustrated in Figure 1 (Vangeem et al., n.d.). A dramatic experience of this is walking into a parking garage on a hot summer day and noticing the temperature is much cooler in the garage than outside, even though the garage has no mechanical air conditioning. The heat will then slowly transfer, and it will be warmer in the garage than outside at night. This effect will create reductions in peak heating and cooling loads and reductions in measured energy. This works well in commercial applications by delaying the peak summer load, generally around 3:00 pm, to later in the evening when offices begin to close.

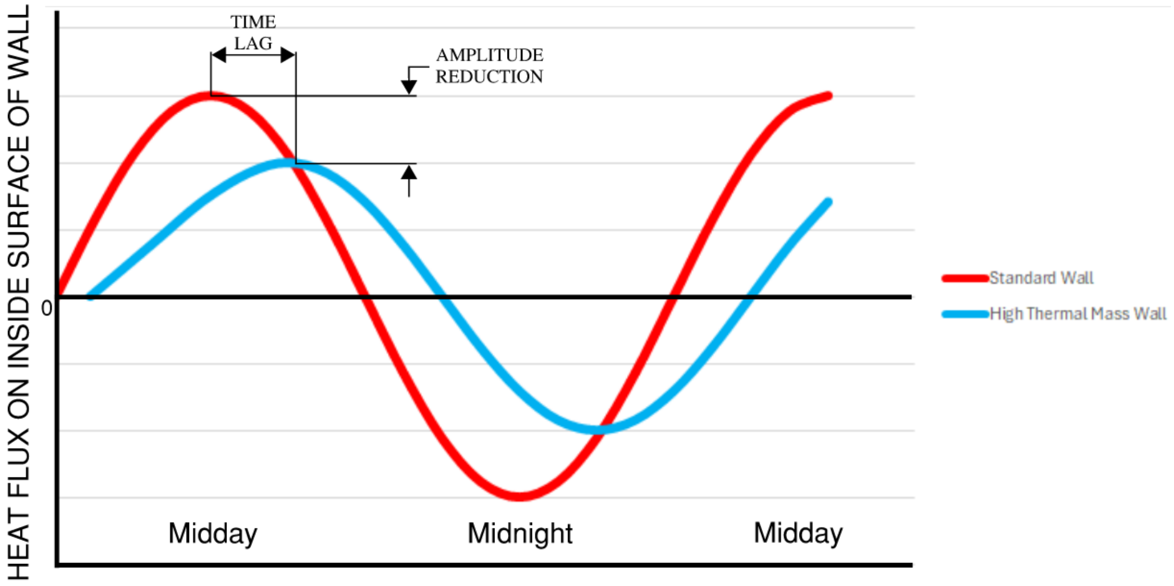


Figure 1: Thermal Mass of Standard Wall Vs. High Thermal Mass Wall

Thermal mass and thermal inertia provide different sources of thermal efficiency. Thermal mass describes the ability of a material to store heat, while thermal inertia describes heat flow through a material. Thicker concrete walls and higher densities result in more heat storage and higher thermal mass. Thermal inertia is the combined effect of heat storage and movement of heat through a wall. These two properties can be quantified through thermal diffusivity. This is the measure of how quickly a material changes temperature. Knowing this property helps to better calculate the amount of thermal lag a material has and how long it will take for the heat to transfer through fully. High thermal diffusivity indicates that temperature change through a material will be fast. This is related to a material's thermal conductivity and specific heat. With high specific heat and low conductivity, concrete has a low thermal diffusivity, which allows it to create longer thermal lag in structures. Quality thermal mass is an attribute that represents the best combination of density, specific heat capacity, and thermal conductivity.

Optimal Thermal Mass

Finding an optimal combination of thermal mass and thermal inertia for a particular climate will result in the most efficient design. The change in heat distribution concerning the concrete density is not linear, as shown in Figure 2 (Vangeem et al., n.d.). This is because thermal conductivity increases exponentially compared to density. The increase in thermal conductivity will cause the thermal lag to decrease.

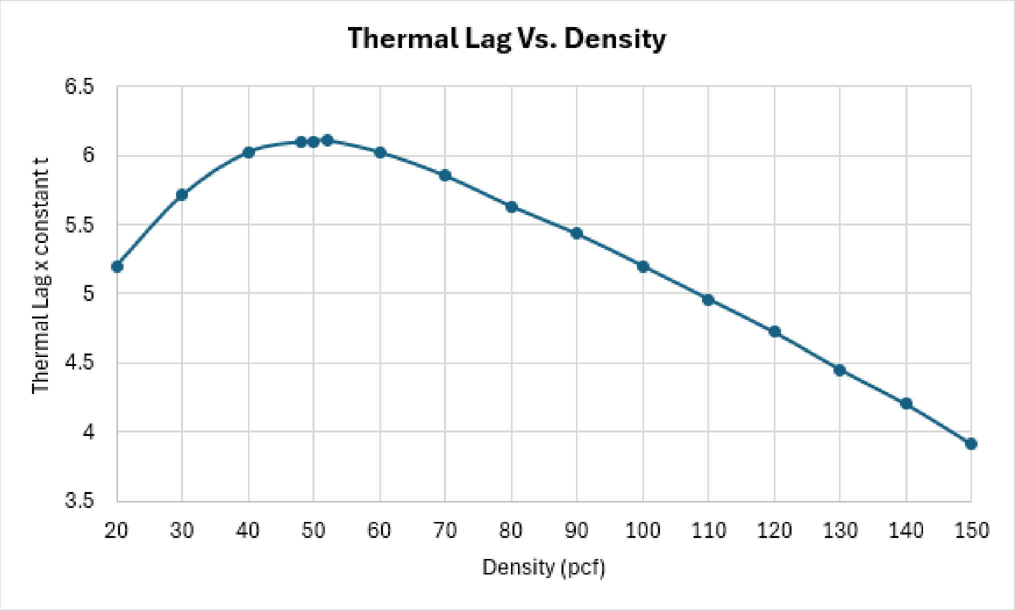


Figure 2: Thermal Lag Vs. Density

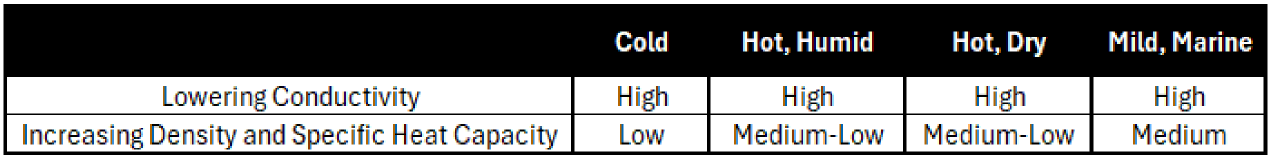
This means that although more density means more thermal storage, which increases the thermal mass, thermal inertia will decrease. With a reduction in density, such as in lightweight concrete, the impacts of thermal inertia on concrete walls are magnified. The thermal conductivity of concrete is inversely proportional to density; although more density creates higher thermal mass, it decreases the distance that the energy must travel. The key to the most efficient design is finding the optimum amount of thermal storage and inertia. The heat must pass through the material slowly while maintaining a high heat storage capacity. A solution to increase thermal lag without changing density is to increase the distance the heat must travel. This can be done by increasing the thickness of the concrete walls or slabs. Doing this allows thermal storage in density to remain constant while the thermal lag increases in the structure, creating more energy efficiency.

Chapter 4: Integrating Thermal Mass

Integrating thermal mass into concrete design will significantly enhance a structure's energy efficiency and sustainability. To achieve optimum energy efficiency, the thermal mass must be integrated appropriately. Designing for high thermal mass will require more material. This will mean more upfront costs and embodied carbon from increased concrete production. However, the higher thermal mass will contribute to lowering the project's overall carbon footprint by improving the building's thermal performance and operational carbon output.

For thermal mass to be effective in buildings, it should be distributed over a large area like floors and walls. Individual components such as columns and beams are less effective. Use wall and floor construction types that provide high thermal mass, such as concrete and stone. The most effective forms of thermal mass are a concrete slab floor, solid concrete walls, and concrete walls in combination with insulation. These are the easiest ways to distribute heat over a large mass. Large areas of mass at a time will prevent thermal bridging and heat loss. Concrete slabs are usually poured on grade, forming the lowest building level, and can be used as a topping for floor systems. Poured concrete walls are another application that effectively exposes the thermal mass to the inside and allows the heat to be distributed throughout the building. When the thermal mass member is exposed to the interior air, it is the most effective for passive heating and cooling. This is best for taking heat out of an area. Even if it is not exposed to indoor air, the thermal mass still greatly regulates the temperature by slowing down heat transfer. These systems, in combination with insulation, will provide the most benefit regarding thermal mass. Adding to the overall thermal mass can be done in multiple ways, such as using more wall space or adding extra thickness to the slabs and walls. This practice can go hand in hand with passive heating and cooling practices such as building orientation and glazing percentages. In this report, a case study is performed to investigate the effects of increased thermal mass in concrete walls versus the thermal and energy performance of buildings in different geographical locations throughout the United States. This is done by comparing a structure's carbon and energy outputs using various concrete wall sections and thicknesses. Increasing the distance the heat must travel is beneficial to decrease thermal conductivity, so increasing the members' thickness slightly can add more heat storage and decrease thermal conductivity.

The climate zone will play a large role in the effectiveness of thermal efficiency. Residential and commercial buildings consume 41% of the total energy used by all sectors of the economy (Ghattas et al., 2013), with most of the energy consumption coming from heating loads. Structures in colder climates generally use more energy than homes in warmer climates. Thermal mass is expected to perform well in temperatures above the comfort zone during the day and below at night, a large temperature variation. This allows the material to function as a heat sink, store heat during the day, and then function as a heat source and slowly release it at night. This illustrates that cold climate projects will benefit the most in the summer, and the warmer climates will benefit more in the winter. Thermal mass benefit in a hot climate is 4.9% energy savings annually, with more significant energy savings in the winter (Ghattas et al., 2013). In colder climates, the annual range of benefits is only 1.5% energy savings, with the most significant impact being in the summer. To have an effective thermal mass design, high density/specific heat and low thermal conductivity must be linked, but the optimal combination of these will vary depending on the climate. In a typical wall, Table 4 outlines the relative relationship between decreasing conductivity and increasing density and specific heat capacity to improve the wall's energy performance for different climate types (Ghattas et al., 2013).



	Cold	Hot, Humid	Hot, Dry	Mild, Marine
Lowering Conductivity	High	High	High	High
Increasing Density and Specific Heat Capacity	Low	Medium-Low	Medium-Low	Medium

Table 4: Optimization of Thermal Mass Properties based on Climate.

Summarizing the information from Table 4 and the properties discussed in Chapter 3, increasing specific heat and density will reduce energy consumption annually if the thermal conductivity is kept constant. There are also scenarios where reducing the thermal conductivity alone will reduce energy consumption. Climate is a key factor in determining the optimal thermal mass design. The same design will behave differently and have different benefits depending on the geographical location.

In optimizing the thermal efficiency of a building, it is important to incorporate both thermal mass and added insulation. Building insulation materials such as fiberglass, mineral wool, and cellulose have relatively high R-values, so they are very resistant to heat flow. Concrete's R-value is low comparatively, but what it lacks in heat flow resistance makes up for in high thermal mass properties and low thermal conductivity. A "happy medium" between the two can create the most efficient design based on resistance and cost savings. ASHRAE Standard 90.1 – Energy Standard for Buildings except Low-Rise Residential and other energy codes recognize the benefits of thermal mass and require less insulation for mass walls. Insulated concrete panel (ICP) walls combine the high thermal mass effects of concrete with the thermal resistance of insulation. This system consists of a layer of insulation sandwiched by concrete panels on either side—a thin concrete panel on the exterior with a larger panel on the interior.

This design exposes the thermal mass to the interior and exterior while adding thermal resistance. These walls can be designed for structural, architectural, or combined purposes.

Evaluating Solutions to Increase Thermal Mass

Increasing the thermal mass properties of a material can potentially increase thermal storage without increasing the actual size of the members. Modifying the core properties of density, specific heat capacity, and thermal conductivity can alter the overall thermal mass. The goal in increasing thermal mass is to have material that can absorb large quantities of heat energy and then store and slowly release this energy. Objects with a higher specific heat capacity require a greater change in energy to change their internal temperature; this allows concrete to regulate more extreme temperatures. Increasing concrete-specific heat capacity can be beneficial for scenarios where greater heat storage and higher thermal mass are essential. However, some trade-offs often involved with increased specific heat capacity include strength, durability, and costs because changing this property involves changing the concrete mix.

Solutions to Increase Specific Heat Capacity:

- Increase Density: Increasing the overall density of the concrete mix will result in increased specific heat capacity because heat will be transferred more slowly through the denser material. This can be done by adding higher density aggregates to the mix. High-density aggregates comprise of more dense minerals, rocks, or even steel and iron substitutes. High-density concrete is often used when the thickness of walls needs to be decreased while maintaining the same strength. Increasing the density will increase the thermal conductivity, which is a downside for the most effective thermal mass. Density increases the thermal storage of a material solely but does not contribute to slowing down heat transfer.

- Increased Water Content: Water has a very high specific heat capacity; therefore, increasing the amount of water in the concrete mix can also improve heat capacity. Water transfers heat at a higher rate than air due to the hydrogen bonds and has a higher storage heat capacity. This solution would increase thermal storage and conductivity, lowering the thermal mass's effectiveness by adding more density. Adding more water content to a concrete mix can lower the compressive strength and durability while changing the workability.

Changing the physical properties of concrete will change the thermal mass effect. Depending on the situation, it will also change the concrete strength and quality properties, which can be beneficial or harmful depending on the design situation. The case study in this report will focus on changing the member sizes while keeping the concrete mix constant, but there are always multiple options to consider. The mass must become larger to increase the thermal mass within a structure without changing the concrete properties. To increase mass, increase the surface area in which the heat energy can be absorbed or increase the distance the heat must travel between spaces. Increasing the surface will increase heat storage availability, while increasing the thickness or distance will decrease the heat transfer speed, providing a better thermal lag between spaces. Thicker walls and more mass come with more weight. This increased load will impact other member sizes, such as columns and foundations, further increasing a project's concrete content. The benefits will be seen in these larger sections, which include the ability to affect a space's thermal efficiency positively.

Chapter 5: Design Parameters

To visualize the concept of thermal mass within concrete walls, a case study was performed to investigate the effects of using increased thermal mass in concrete walls versus the thermal and energy performance of buildings in different geographical locations throughout the United States. The model is based on a simplified two-story steel framed structure with a composite floor system and cast-in-place concrete walls. The footprint is 30 feet by 30 feet with 10-foot wall heights. This will provide 2400 square feet of wall space to use for changing the thermal mass. This frame system was chosen so the conditions of the concrete walls could be changed without drastically affecting the rest of the structure. This is to see the impact that concrete and insulation can have on the thermal efficiency of a building. Grade beams support the first-floor walls, and spread footings under the columns will take the total weight of the structure. The façade and other common wall additions will be considered constants for every test; only the concrete wall thickness will change. The results of three different wall thicknesses, 6-inch, 8-inch, and 12-inch, along with a built-up insulated concrete panel wall section, are compared by carbon emission output, energy demand, and overall cost in various climate regions. The insulated panel wall will have 3 inches of concrete on the exterior, 9 inches on the interior, and 2 inches of R-20 board insulation. This wall will be compared to illustrate the full effect of increased thermal mass combined with insulation. Increased wall thickness and additional thermal mass will consequently increase the material quantity and self-weight of the structure. The extra weight will increase foundation sizes. The additional structure and material will also increase the structure's embodied carbon. The climate regions are based on three conditions: heating-dominated, temperate, and cooling-dominated. The locations will be Minneapolis, MN, Manhattan, KS, and Phoenix, AZ, respectfully. The purpose of this design is not to show specifics but to illustrate a trend. The study looks at high thermal mass design's cost and CO2 impact.

To design the constants of the structure, a floor dead load of 25 lb/ft^2 and a live load of 100 lb/ft^2 are used. The live load is on the higher end to encompass a variety of situations and model more realistic foundation sizes. A roof live load of 20 lb/ft^2 and a roof dead load of 20 lb/ft^2 simulate a general roof system. These loads are based on standard values from ASCE 7-22 (ASCE, 2021). The composite floor system comprises a 3-inch metal deck with 4 inches of normal-weight concrete. This system, chosen from the Vulcraft manual, can resist the loads provided and adequately support an infill beam spacing of 10’-0” for the 30-foot bay. Its self-weight is 69 lb/ft^2. On the ground level, there is a 6-inch slab on grade. These parameters and systems will remain constant throughout the different wall types.

Hand calculations were used to get spread footing and grade beam sizes for the different wall sizes to create an accurate, simplified structure. The foundation members slightly increase with the increase in the structure's self-weight. This structure is very small-scale, so the increase is minimal. However, on taller projects, the increase in foundation sizes will become more significant, and so will the thermal mass. To calculate the total concrete quantity of the structure, the cast-in-place concrete walls, concrete of the composite floor, slab on grade, grade beams, and spread footings are considered. The volume of concrete needed is calculated, and then an estimated carbon impact is calculated using SEI’s ECOM (Embodied Carbon Order of Magnitude) calculator. The increase in concrete quantity is linearly related to the carbon impact. ECOM is a basic embodied carbon estimator that allows users to determine approximate embodied carbon values for materials and assemblies. The underlying data has been gathered by the Structural Engineering Institute from available industry-wide environmental product declarations that apply to North America. In addition, RS-Means is used to estimate the cost of the concrete material and labor required to construct the different members. There are costs associated with each element. RS-Means is a database of current construction cost estimates based on U.S. national averages (The Gordian Group, 2023). Location factors can adjust these cost values based on a certain geographical region's material and labor costs. The cost of design will be compared by wall thickness and location. The 2023 edition of RS-Means is used for this case study.

eQuest measures the structure's operational energy usage, including the annual electricity used for heating and cooling. The program uses a building's location weather data to create accurate energy loads based on its structure and systems. eQuest uses the envelope's U-values (thermal transmittance) to account for the thermal mass effect in a building. The U-value is the reciprocal of the R-value. The annual electricity usage, in kilowatt-hours, is used to calculate the carbon impact based on U.S. Energy Information Administration (EIA) data (*U.S. Energy Information Administration (EIA)*, n.d.). According to the EIA, 0.86 pounds of CO2 is produced per kWh of electricity based on all energy sources. This value is used to calculate the total emissions for the structure based on energy use. A building has many variable electricity factors, from mechanical equipment to lighting needs. The heating, cooling, and electricity loads are based on a small office building. The values used for eQuest parameters are based on ASHRAE Standard 90.1 2022 edition. The default setting is used for most of the design and remains constant throughout the design variations. The only variables that change are the thickness of the concrete walls and the location. The HVAC system is a split, single-zone DX with electric heat and a ducted return air path. It uses DX coils for cooling and electric resistance for heating.

eQuest auto-sizes the system for the applicable structure. Utility costs for each location are based on information from the EIA.

The insulated concrete panel wall (ICP) combines the high thermal mass properties of concrete with the thermal resistance of insulation. This case is run to illustrate the full effect of the combination. The results for this case should not be directly compared to the others because the others are looking at the concrete wall alone. Standard rigid board insulation used in concrete sandwich panels is polyurethane and polyisocyanurate. These materials have a closed-cell composition with lower thermal conductivity. The energy needed to produce these materials creates initial embodied carbon. The embodied carbon content of insulation can vary widely depending on the type. The wall for this study will use two inches of EPS (expanded polystyrene insulation) Type 1 closed-cell rigid foam board with an R-value of 20 that has roughly 5.5 pounds of CO2 per square foot of wall space (Waldman et al., 2023).

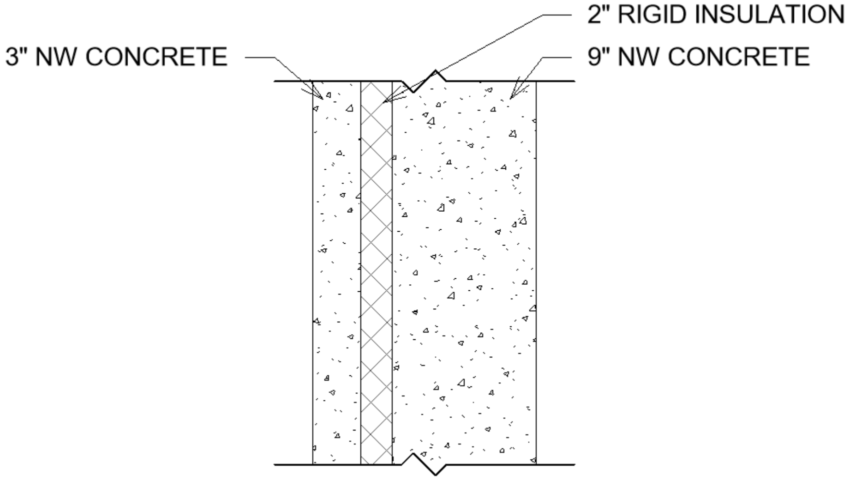


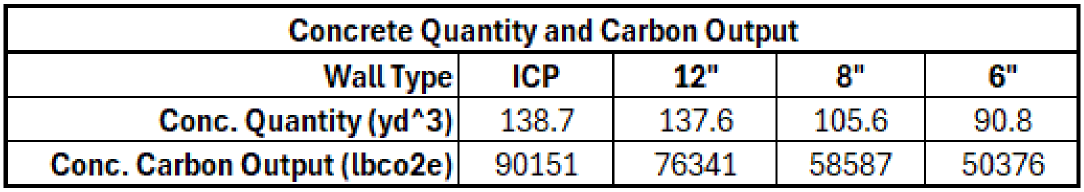
Figure 3: Insulated Concrete Panel Section

These tools were used to analyze the four different wall types based on concrete quantity, concrete carbon emissions, annual energy usage, annual utility costs, and annual energy carbon emissions. Along with these parameters, a life-cycle assessment of the operational carbon and utility costs is analyzed to illustrate the effectiveness over time. According to the EIA, electricity prices in the United States have increased by 2.67% annual per year over the past 25 years. The life cycle analysis will be based on 25 years at a 2.67% inflation rate. This design set is run for three regions: Minneapolis, MN; Manhattan, KS; and Phoenix, AZ. The results compare different wall types (thermal mass quantity) to each other and in different climate regions to find the most effective thermal mass design. The findings from the case study indicate that thermal mass positively affects a building’s energy demand.

Chapter 6: Results

Concrete Results

The concrete quantity was calculated based on volume in cubic yards to establish the structure's embodied carbon. The ECOM calculator uses this volume to calculate the carbon content in pounds of CO2. The concrete quantity and carbon content do not depend on the region and will be constant for each climate tested. The differences are seen when changing the wall types. The concrete quantity and associated carbon content for the different wall types are illustrated in Table 5. The calculations for concrete quantity and construction costs are presented in Appendix A.



Concrete Quantity and Carbon Output				
Wall Type	**ICP**	**12"**	**8"**	**6"**
Conc. Quantity (yd^3)	138.7	137.6	105.6	90.8
Conc. Carbon Output (lbco2e)	90151	76341	58587	50376

Table 5: Concrete Constants Outputs

Increasing the structure's thermal mass and concrete quantity will affect the foundation members. The sizes of foundation members for each wall type are as follows:

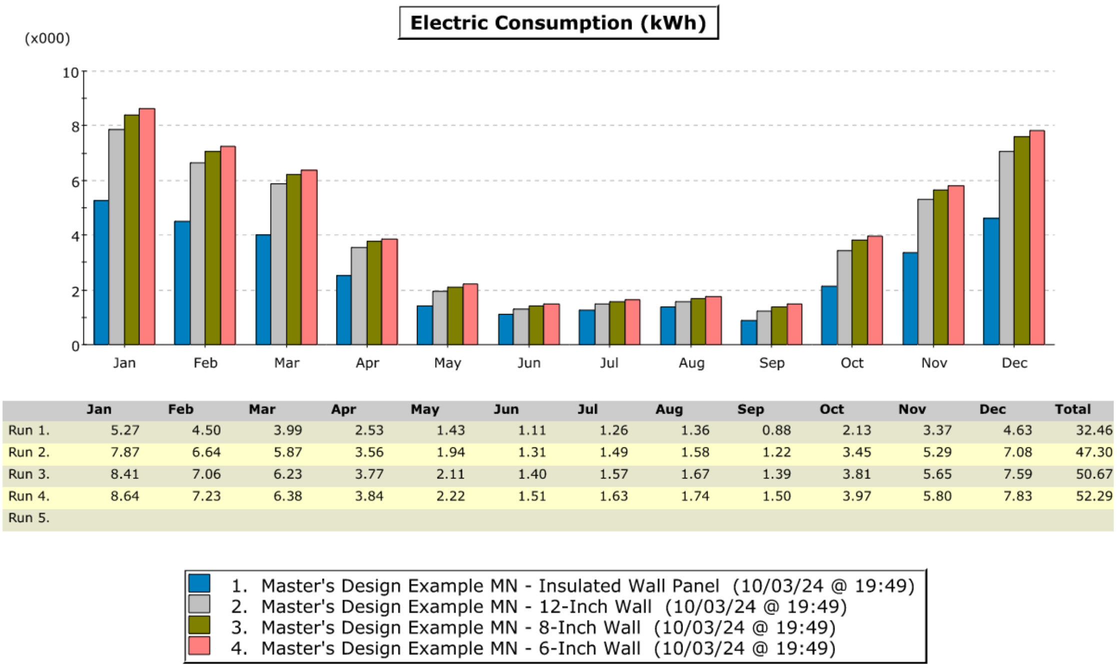
- 6-Inch Wall:
  - Spread Footing: 8’ x 8’ x 16”
  - Grade Beam: 16” x 12”
- 8-Inch Wall:
  - Spread Footing: 8’ x 8’ x 16”
  - Grade Beam: 16” x 12”

- 12-Inch Wall:
    - Spread Footing: 8’ x 8’ x 18”
    - Grade Beam: 18” x 12”
- Insulated Concrete Panel Wall:
    - Spread Footing: 8’ x 8’ x 18”
    - Grade Beam: 18” x 14”

The increase in foundation members is minimal when considering a small building footprint. Slight increases in wall thickness, such as the 6-inch wall compared to the 8-inch wall, will have little to no effect on the foundations, and the only increase in concrete quantity will be from changing the wall thickness. Making a larger change in wall thickness will increase the size of foundation members due to a larger increase in self-weight. Based on the hand calculation data, effects on foundation members will be more largely seen in buildings with larger footprints. The increase in wall self-weight will have an exponentially larger impact when the surface area of the walls increases. There is a linear increase in carbon quantity and content when the foundation members are unchanged between wall thicknesses. Between the 6-inch and 8-inch walls, the concrete quantity increases at 7.4 cubic yards per inch, increasing 4105.5 lbCO2e per inch of added concrete. As the wall thickness becomes more significant and the foundation members increase, the embodied carbon will start to increase exponentially with larger changes in foundation sizes. The difference between the 12-inch and 8-inch walls is 8.0 cubic yards per inch and 4438.5 lbCO2e per inch of concrete. The insulated panel is 14 inches thick, will require the most concrete quantity due to the demand for a wider grade beam, and will produce the most embodied carbon emissions due to the added emissions from the insulation and highest concrete quantity. The insulation creates about a 16% increase in embodied carbon.

Minneapolis, MN

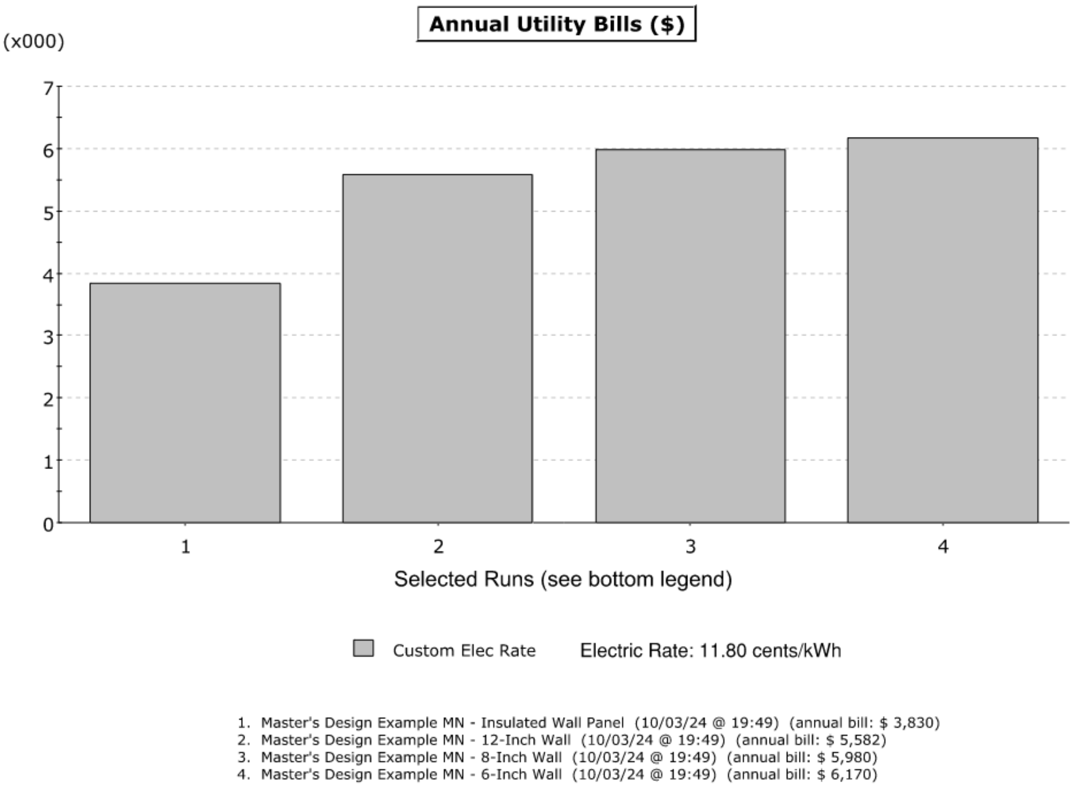
The concrete quantity, carbon emissions, annual energy usage, annual utility costs, and annual energy carbon emissions are analyzed for the different wall types based on the climate region. Minneapolis, MN, is located in the northern part of the United States and is considered a heating-dominated, or colder, climate. This area is known for wide temperature swings from summer to winter. East Central Energy is a cooperative-owned utility that supplies electricity to Minneapolis at 11.80 cents per kilowatt-hour, the highest among the three regions analyzed. This area also experiences the highest heating energy demands. According to RS-Means, the location factor for Minneapolis is 1.07, making it the highest of the three regions evaluated. This means labor costs and material costs for this location are greater than the average. These results are compared to find the optimum thermal mass design. The eQuest energy outputs for Minneapolis, MN, are illustrated in Figures 4 and 5. The total values for embodied carbon, operational carbon, and associated costs are compiled in Table 6 and then Figure 6 illustrates a comparison of embodied carbon to operational carbon. The inputs into eQuest to obtain these results is provided in Appendix B.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Run 1.	5.27	4.50	3.99	2.53	1.43	1.11	1.26	1.36	0.88	2.13	3.37	4.63	32.46
Run 2.	7.87	6.64	5.87	3.56	1.94	1.31	1.49	1.58	1.22	3.45	5.29	7.08	47.30
Run 3.	8.41	7.06	6.23	3.77	2.11	1.40	1.57	1.67	1.39	3.81	5.65	7.59	50.67
Run 4.	8.64	7.23	6.38	3.84	2.22	1.51	1.63	1.74	1.50	3.97	5.80	7.83	52.29
Run 5.													

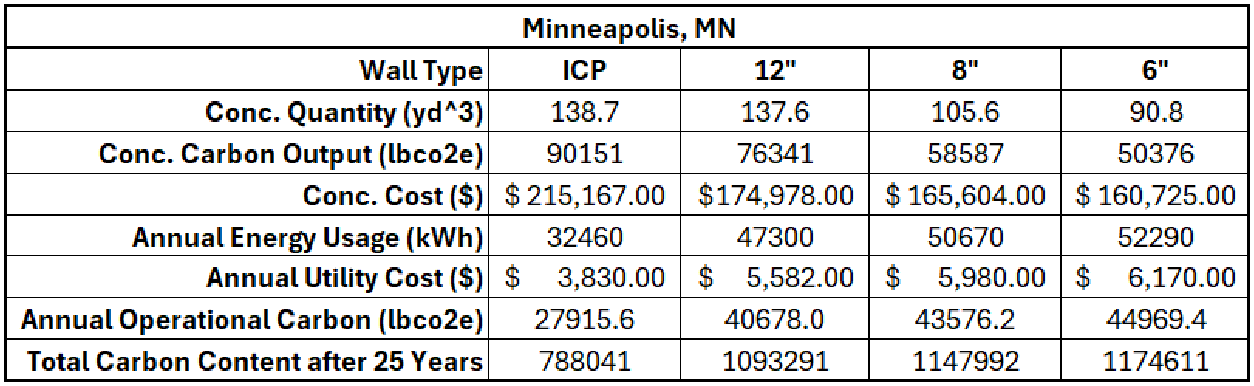
1. Master's Design Example MN - Insulated Wall Panel (10/03/24 @ 19:49)
2. Master's Design Example MN - 12-Inch Wall (10/03/24 @ 19:49)
3. Master's Design Example MN - 8-Inch Wall (10/03/24 @ 19:49)
4. Master's Design Example MN - 6-Inch Wall (10/03/24 @ 19:49)

Figure 4: Electric Consumption for Minneapolis



1. Master's Design Example MN - Insulated Wall Panel (10/03/24 @ 19:49) (annual bill: $ 3,830)
2. Master's Design Example MN - 12-Inch Wall (10/03/24 @ 19:49) (annual bill: $ 5,582)
3. Master's Design Example MN - 8-Inch Wall (10/03/24 @ 19:49) (annual bill: $ 5,980)
4. Master's Design Example MN - 6-Inch Wall (10/03/24 @ 19:49) (annual bill: $ 6,170)

Figure 5: Annual Utility Bill for Minneapolis



Minneapolis, MN				
Wall Type	ICP	12"	8"	6"
Conc. Quantity (yd^3)	138.7	137.6	105.6	90.8
Conc. Carbon Output (lbco2e)	90151	76341	58587	50376
Conc. Cost ($)	$ 215,167.00	$174,978.00	$ 165,604.00	$ 160,725.00
Annual Energy Usage (kWh)	32460	47300	50670	52290
Annual Utility Cost ($)	$ 3,830.00	$ 5,582.00	$ 5,980.00	$ 6,170.00
Annual Operational Carbon (lbco2e)	27915.6	40678.0	43576.2	44969.4
Total Carbon Content after 25 Years	788041	1093291	1147992	1174611

Table 6: Minneapolis, MN Results

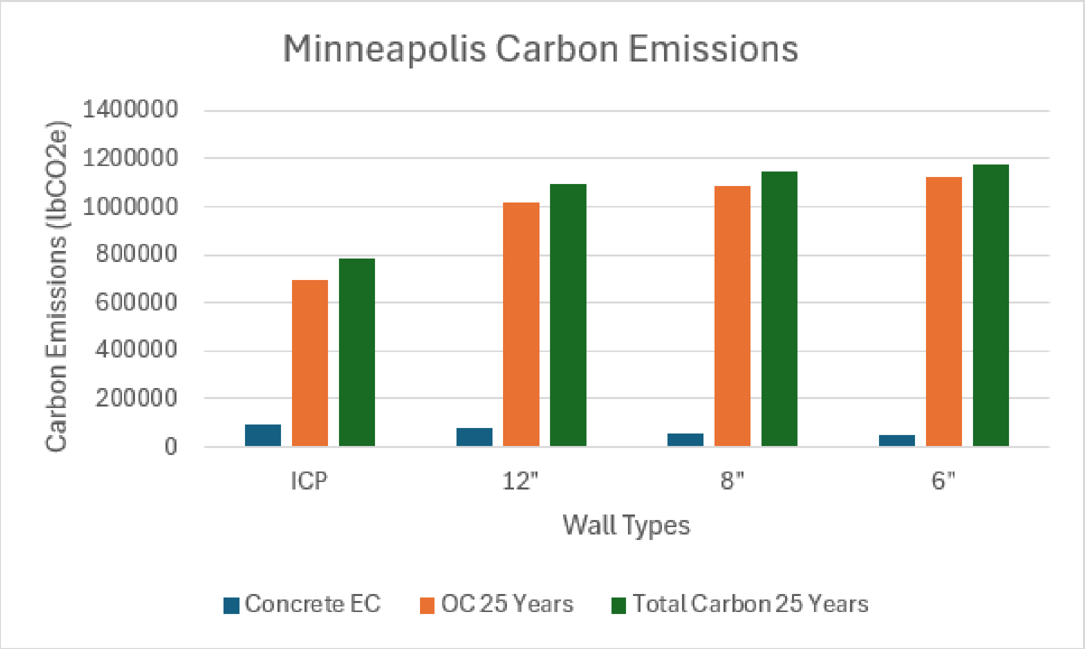
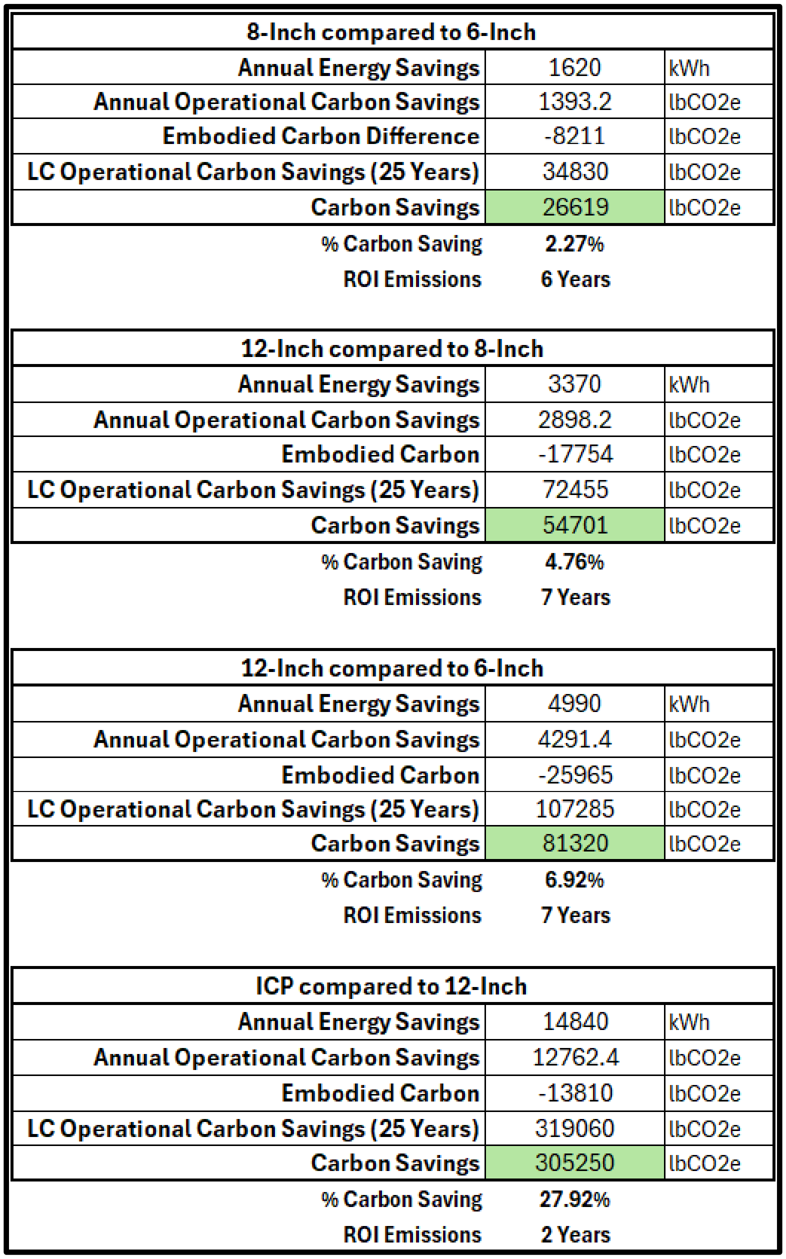


Figure 6: Carbon Emission Comparisons for Minneapolis, MN

Increasing the thickness of the concrete wall results in increased concrete quantity, embodied carbon, and concrete initial costs while decreasing annual energy usage, utility costs, and operational carbon. The majority of the life cycle carbon in the first 25 years comes from the operational carbon, which is the heating and cooling needs of a building. As the thickness of the walls increases and there is more thermal mass, the total carbon footprint of the project decreases. The following tables 7, 8, and 9 will compare each wall type and the associated savings in carbon emissions and costs through the first 25 years caused by increased thermal mass.



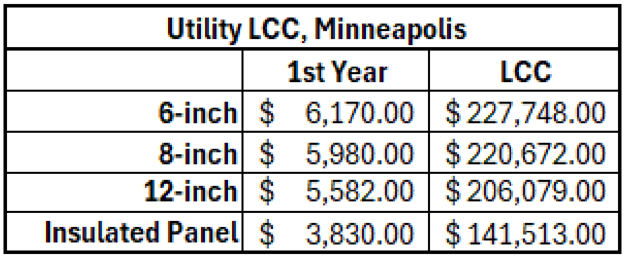
8-Inch compared to 6-Inch		
Annual Energy Savings	1620	kWh
Annual Operational Carbon Savings	1393.2	lbCO2e
Embodied Carbon Difference	-8211	lbCO2e
LC Operational Carbon Savings (25 Years)	34830	lbCO2e
Carbon Savings	26619	lbCO2e
% Carbon Saving	**2.27%**	
ROI Emissions	**6 Years**	

12-Inch compared to 8-Inch		
Annual Energy Savings	3370	kWh
Annual Operational Carbon Savings	2898.2	lbCO2e
Embodied Carbon	-17754	lbCO2e
LC Operational Carbon Savings (25 Years)	72455	lbCO2e
Carbon Savings	54701	lbCO2e
% Carbon Saving	**4.76%**	
ROI Emissions	**7 Years**	

12-Inch compared to 6-Inch		
Annual Energy Savings	4990	kWh
Annual Operational Carbon Savings	4291.4	lbCO2e
Embodied Carbon	-25965	lbCO2e
LC Operational Carbon Savings (25 Years)	107285	lbCO2e
Carbon Savings	81320	lbCO2e
% Carbon Saving	**6.92%**	
ROI Emissions	**7 Years**	

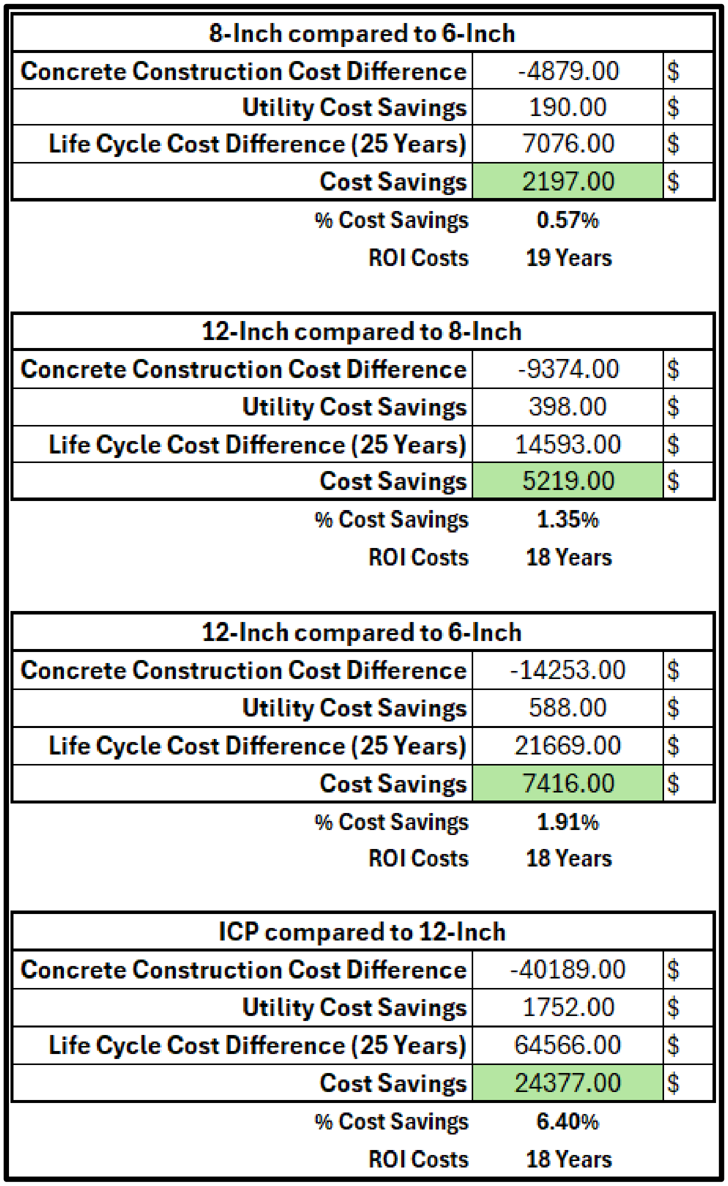
ICP compared to 12-Inch		
Annual Energy Savings	14840	kWh
Annual Operational Carbon Savings	12762.4	lbCO2e
Embodied Carbon	-13810	lbCO2e
LC Operational Carbon Savings (25 Years)	319060	lbCO2e
Carbon Savings	305250	lbCO2e
% Carbon Saving	**27.92%**	
ROI Emissions	**2 Years**	

Table 7: Energy and carbon savings between wall types for Minneapolis: (negative entries indicate increased carbon)



Utility LCC, Minneapolis		
	1st Year	LCC
6-inch	$ 6,170.00	$ 227,748.00
8-inch	$ 5,980.00	$ 220,672.00
12-inch	$ 5,582.00	$ 206,079.00
Insulated Panel	$ 3,830.00	$ 141,513.00

Table 8: Utility Life Cycle Cost Analysis for Minneapolis



8-Inch compared to 6-Inch		
Concrete Construction Cost Difference	-4879.00	$
Utility Cost Savings	190.00	$
Life Cycle Cost Difference (25 Years)	7076.00	$
Cost Savings	2197.00	$
% Cost Savings	0.57%	
ROI Costs	19 Years	

12-Inch compared to 8-Inch		
Concrete Construction Cost Difference	-9374.00	$
Utility Cost Savings	398.00	$
Life Cycle Cost Difference (25 Years)	14593.00	$
Cost Savings	5219.00	$
% Cost Savings	1.35%	
ROI Costs	18 Years	

12-Inch compared to 6-Inch		
Concrete Construction Cost Difference	-14253.00	$
Utility Cost Savings	588.00	$
Life Cycle Cost Difference (25 Years)	21669.00	$
Cost Savings	7416.00	$
% Cost Savings	1.91%	
ROI Costs	18 Years	

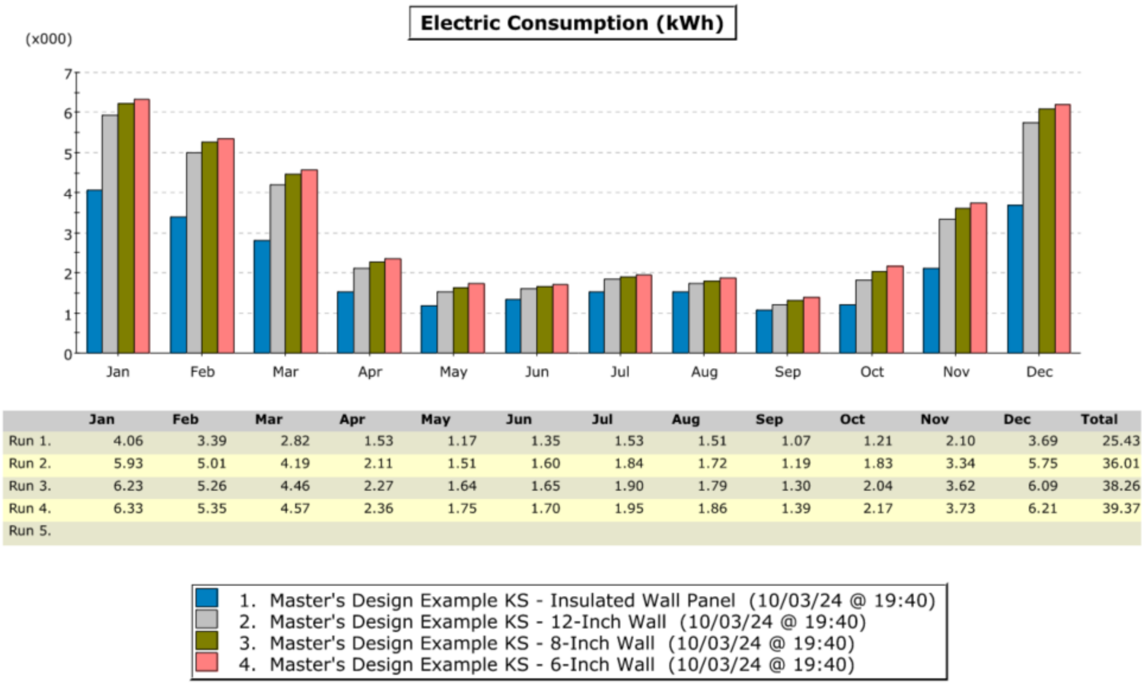
ICP compared to 12-Inch		
Concrete Construction Cost Difference	-40189.00	$
Utility Cost Savings	1752.00	$
Life Cycle Cost Difference (25 Years)	64566.00	$
Cost Savings	24377.00	$
% Cost Savings	6.40%	
ROI Costs	18 Years	

Table 9: Cost savings between wall types for Minneapolis: (negative entries indicate increased costs)

The more significant the increase in thermal mass, the more operational carbon savings and cost savings. The 6-inch wall has the lowest embodied carbon and initial cost but the highest energy demand and significant carbon footprint. Increased thermal mass creates exponential carbon emission reductions and more cost savings for this climate. The initial cost of concrete construction is higher for increased wall thickness, especially in Minneapolis, which has the highest construction costs. However, over 25 years, money has been saved on utility costs for all cases of increasing thermal mass. The return on investment for increasing the thermal mass is 18-19 years for each case. The cost savings are minimal within the first 25 years, under 2% for the concrete-only cases and only 6.4% for the ICP. Nevertheless, they will continue to grow as the life of the building is extended. The energy demand is much more significant in the winter than in the summer months, the winter months saw a greater impact when increasing the thermal mass. For the wall types consisting solely of concrete, the 12-inch wall sees the most significant savings in carbon emissions, with 6.92% less carbon produced than the 6-inch wall. The highest thermal mass design has the most efficiency. The insulated concrete panel wall illustrates the drastic effect adding a small amount of insulation will have on the thermal efficiency of a building. The insulated panel wall has the most significant embodied carbon and initial cost but results in the greatest carbon emissions and cost savings, with 27.92% more carbon emission reductions than the 12-inch wall. The return on investment for the carbon savings in this climate is seen very soon, only 6-7 years for the concrete-only walls and only 2 years for the ICP. This is a quick turnaround for carbon emission savings, and these reductions will continue to increase as the building life is extended.

Manhattan, KS

The same methodology is followed for the temperate region. Manhattan is located in central Kansas and has a climate where the summers can be hot, and the winters will be cold. Evergy Kansas Central provides the electric utility at 11.34 cents/kWh, and the RS-Means location factor is 0.9. These values put the building costs in the middle of the pack compared to the other regions. This building will see a higher energy demand in the winter, and the thermal mass will be most effective in the summer. The eQuest energy outputs for Manhattan, KS, are illustrated in Figures 7 and 8. The total values for embodied carbon, operational carbon, and associated costs are compiled in Table 10 and Figure 9 illustrates a comparison of embodied carbon to operational carbon.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Run 1.	4.06	3.39	2.82	1.53	1.17	1.35	1.53	1.51	1.07	1.21	2.10	3.69	25.43
Run 2.	5.93	5.01	4.19	2.11	1.51	1.60	1.84	1.72	1.19	1.83	3.34	5.75	36.01
Run 3.	6.23	5.26	4.46	2.27	1.64	1.65	1.90	1.79	1.30	2.04	3.62	6.09	38.26
Run 4.	6.33	5.35	4.57	2.36	1.75	1.70	1.95	1.86	1.39	2.17	3.73	6.21	39.37
Run 5.													

Figure 7: Electric Consumption for Manhattan

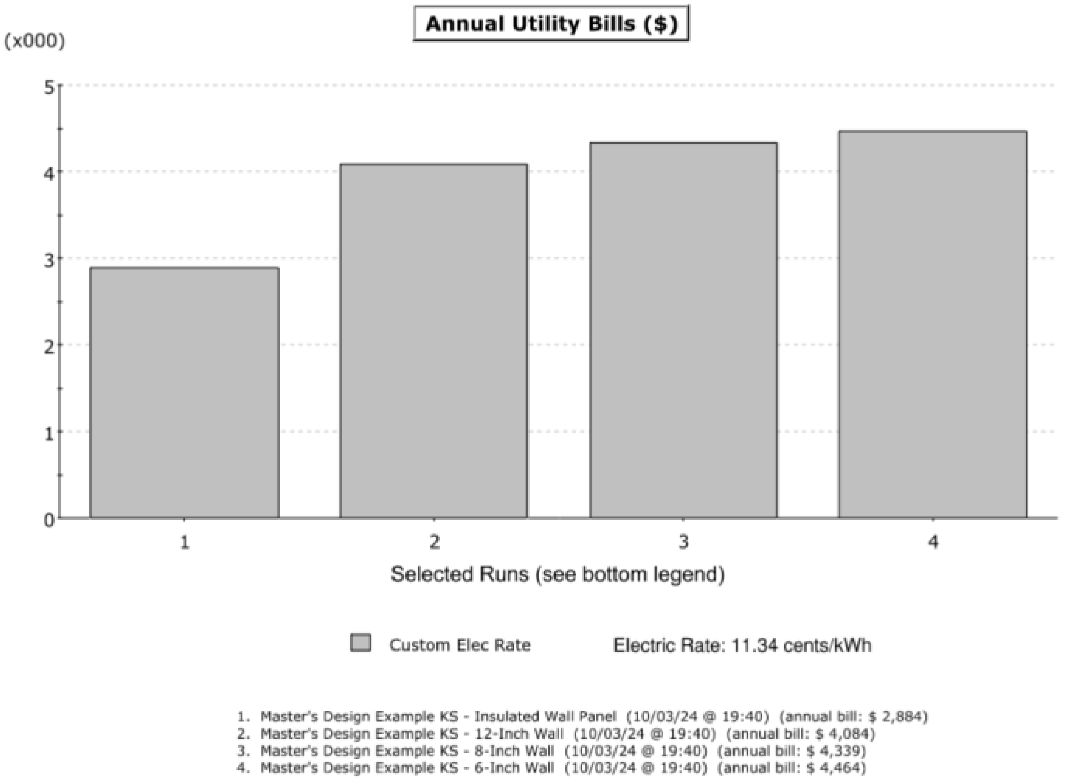


Figure 8: Annual Utility Bill for Manhattan

Manhattan, KS				
Wall Type	**ICP**	**12"**	**8"**	**6"**
Conc. Quantity (yd^3)	138.7	137.6	105.6	90.8
Conc. Carbon Output (lbco2e)	90151	76341	58587	50376
Conc. Cost ($)	$ 180,981.00	$147,177.00	$ 139,293.00	$ 135,189.00
Annual Energy Usage (kWh)	25430	36010	38260	39370
Annual Utility Cost ($)	$ 2,884.00	$ 4,084.00	$ 4,339.00	$ 4,464.00
Annual Operational Carbon (lbco2e)	21869.8	30968.6	32903.6	33858.2
Total Carbon Content after 25 Years	636896	850556	881177	896831

Table 10: Manhattan, KS Results

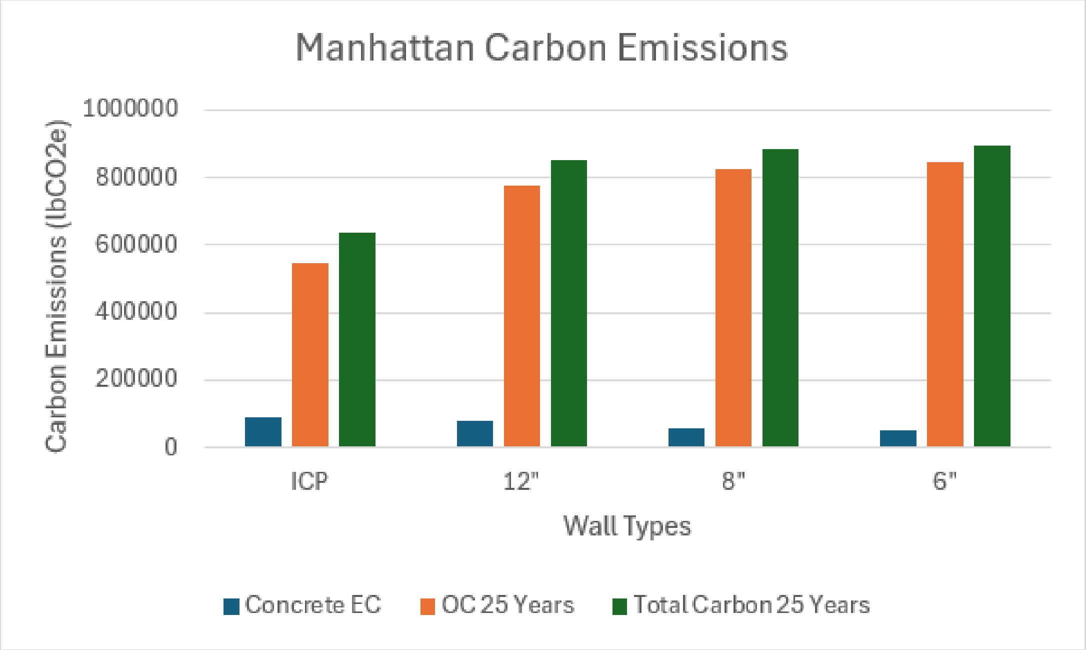
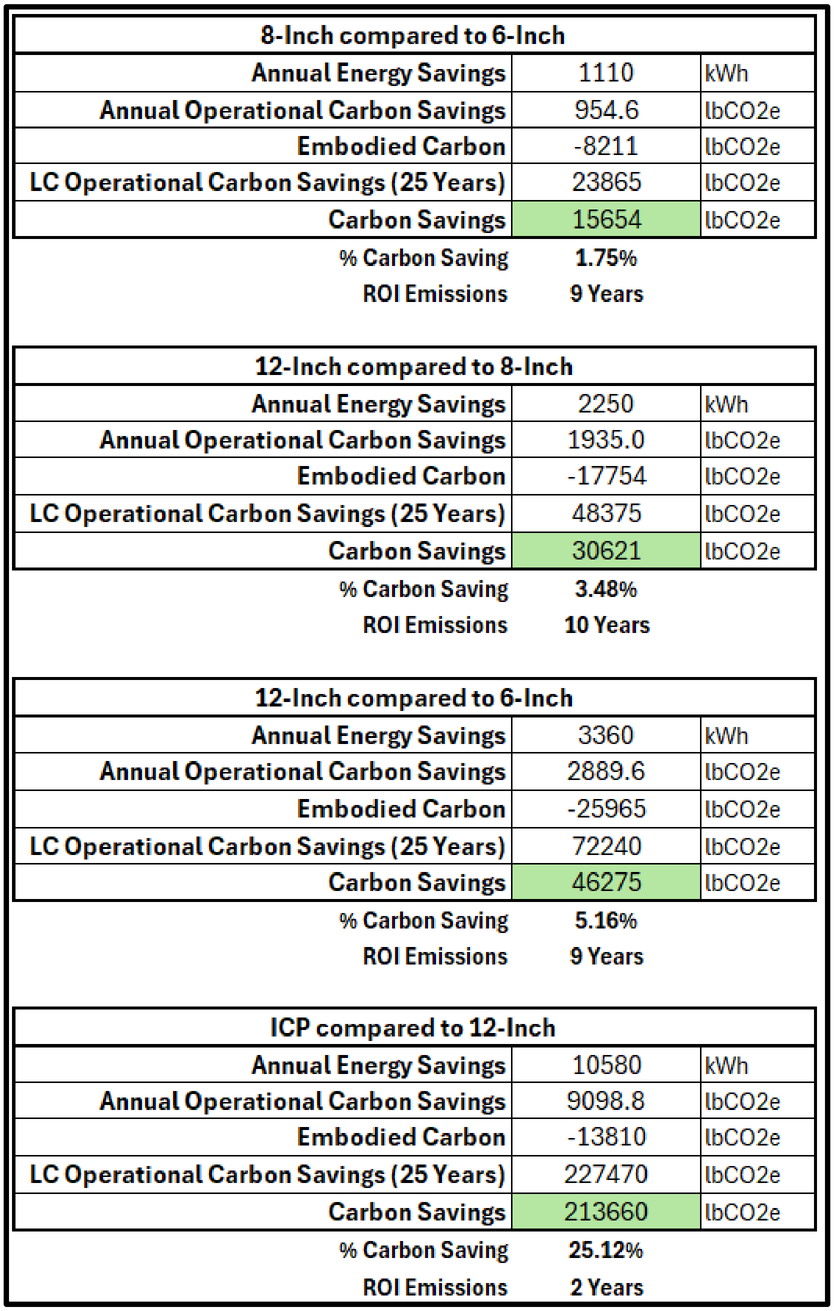


Figure 9: Carbon Emission Comparisons for Manhattan, KS

The results for the Manhattan climate are similar to those of Minneapolis. As the thickness of the walls increases and there is more thermal mass, the project's total carbon footprint decreases. With more significant thermal mass increases, operational carbon savings and cost savings are seen here again for the temperate climate. This makes sense as this is another climate that has a considerable variation between summer and winter. Energy usage is more significant in the winter months than in the summer months. The difference is that the values are lower than those in Minneapolis. The costs are lower due to lower utility costs and location factors; the total amount of energy consumed and operational carbon used is much lower due to less extreme heating loads. The breakdown of each wall type is illustrated in the following tables. The following tables 11, 12, and 13 will compare each wall type and the associated savings in carbon emissions and costs through the first 25 years caused by increased thermal mass.



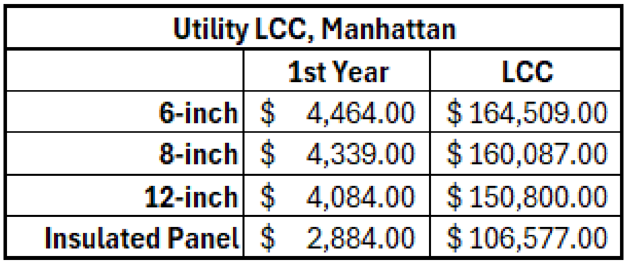
8-Inch compared to 6-Inch		
Annual Energy Savings	1110	kWh
Annual Operational Carbon Savings	954.6	lbCO2e
Embodied Carbon	-8211	lbCO2e
LC Operational Carbon Savings (25 Years)	23865	lbCO2e
Carbon Savings	15654	lbCO2e
% Carbon Saving	**1.75%**	
ROI Emissions	**9 Years**	

12-Inch compared to 8-Inch		
Annual Energy Savings	2250	kWh
Annual Operational Carbon Savings	1935.0	lbCO2e
Embodied Carbon	-17754	lbCO2e
LC Operational Carbon Savings (25 Years)	48375	lbCO2e
Carbon Savings	30621	lbCO2e
% Carbon Saving	**3.48%**	
ROI Emissions	**10 Years**	

12-Inch compared to 6-Inch		
Annual Energy Savings	3360	kWh
Annual Operational Carbon Savings	2889.6	lbCO2e
Embodied Carbon	-25965	lbCO2e
LC Operational Carbon Savings (25 Years)	72240	lbCO2e
Carbon Savings	46275	lbCO2e
% Carbon Saving	**5.16%**	
ROI Emissions	**9 Years**	

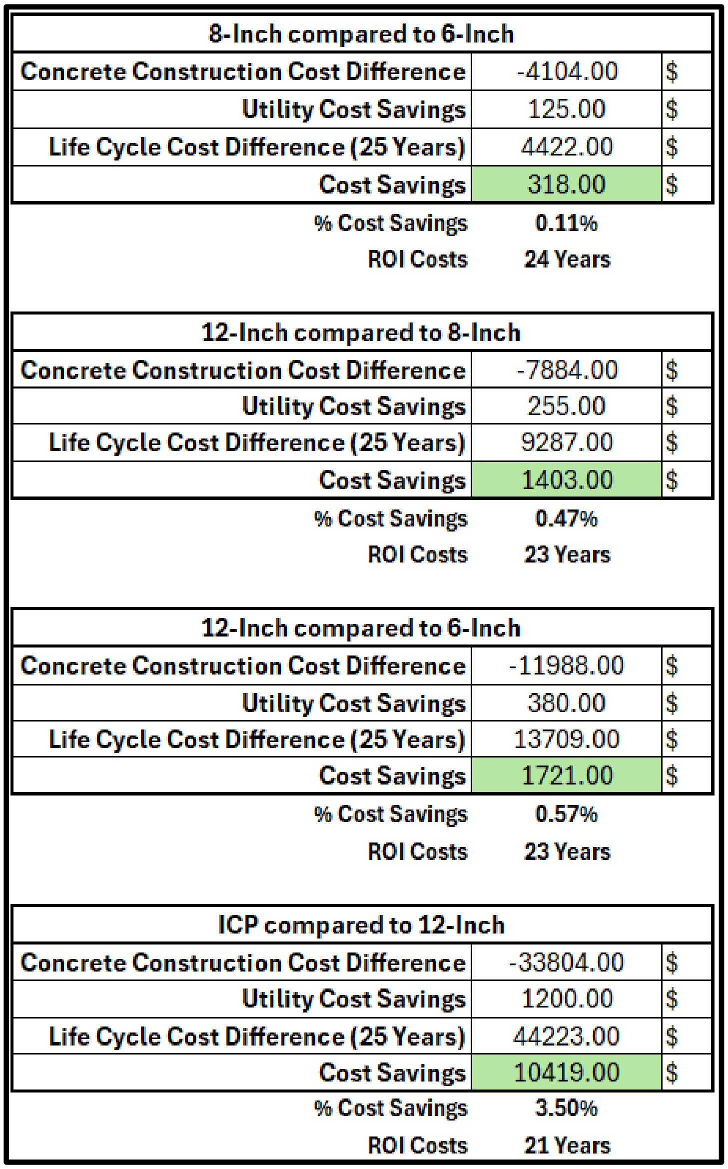
ICP compared to 12-Inch		
Annual Energy Savings	10580	kWh
Annual Operational Carbon Savings	9098.8	lbCO2e
Embodied Carbon	-13810	lbCO2e
LC Operational Carbon Savings (25 Years)	227470	lbCO2e
Carbon Savings	213660	lbCO2e
% Carbon Saving	**25.12%**	
ROI Emissions	**2 Years**	

Table 11: Energy and carbon savings between wall types for Manhattan: (negative entries indicate increased carbon)



Utility LCC, Manhattan		
	1st Year	LCC
6-inch	$ 4,464.00	$ 164,509.00
8-inch	$ 4,339.00	$ 160,087.00
12-inch	$ 4,084.00	$ 150,800.00
Insulated Panel	$ 2,884.00	$ 106,577.00

Table 12: Utility Life Cycle Cost Analysis for Manhattan



8-Inch compared to 6-Inch		
Concrete Construction Cost Difference	-4104.00	$
Utility Cost Savings	125.00	$
Life Cycle Cost Difference (25 Years)	4422.00	$
Cost Savings	318.00	$
% Cost Savings	0.11%	
ROI Costs	24 Years	

12-Inch compared to 8-Inch		
Concrete Construction Cost Difference	-7884.00	$
Utility Cost Savings	255.00	$
Life Cycle Cost Difference (25 Years)	9287.00	$
Cost Savings	1403.00	$
% Cost Savings	0.47%	
ROI Costs	23 Years	

12-Inch compared to 6-Inch		
Concrete Construction Cost Difference	-11988.00	$
Utility Cost Savings	380.00	$
Life Cycle Cost Difference (25 Years)	13709.00	$
Cost Savings	1721.00	$
% Cost Savings	0.57%	
ROI Costs	23 Years	

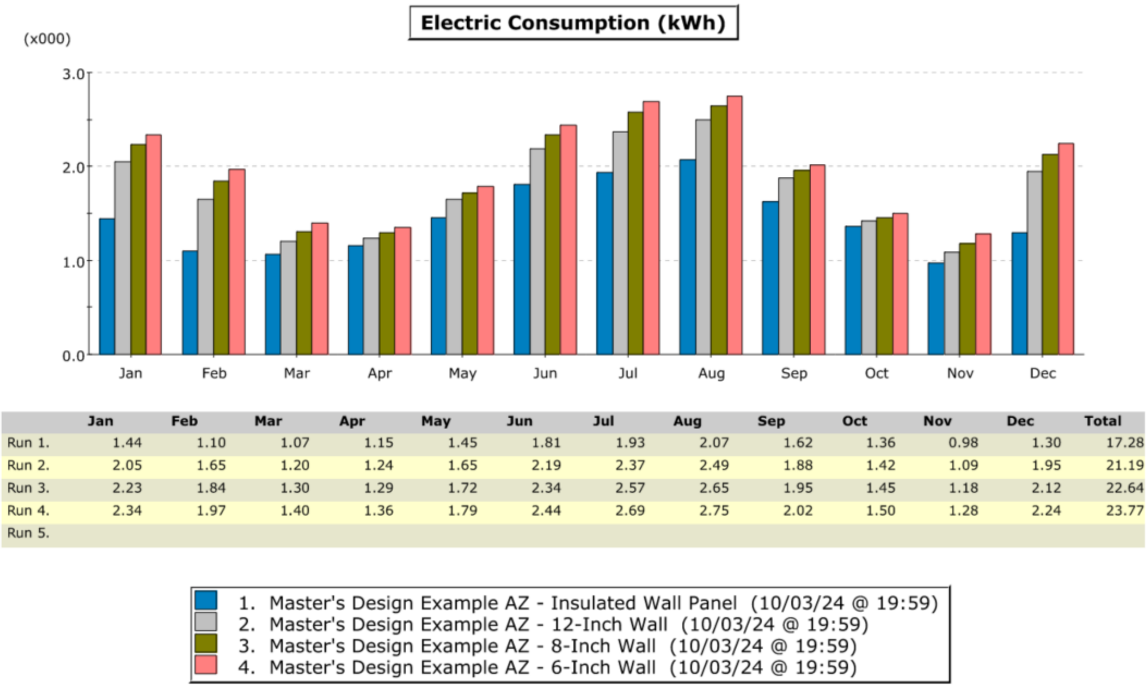
ICP compared to 12-Inch		
Concrete Construction Cost Difference	-33804.00	$
Utility Cost Savings	1200.00	$
Life Cycle Cost Difference (25 Years)	44223.00	$
Cost Savings	10419.00	$
% Cost Savings	3.50%	
ROI Costs	21 Years	

Table 13: Cost savings between wall types for Manhattan: (negative entries indicate increased costs)

Similar to Minneapolis, the more significant the increase in thermal mass, the more operational carbon savings and cost savings. The 6-inch wall still has the highest cost and most minor emission reductions, while the 12-inch wall is the most effective, aside from the insulated concrete panel wall, which is still highly effective for temperate climates. The difference from the colder climate is that the reductions in carbon emissions and cost savings are less significant. The 12-inch wall has 5.16% less carbon emission content than the 6-inch wall, and the return on investment of carbon emissions has increased slightly to 9-10 years for concrete-only cases, remaining at 2 years for the ICP. The insulated concrete panel wall still sees heavy reductions, with 25.12% less carbon content than the 12-inch wall. Increasing thermal mass in the temperate climate is still practical but slightly less effective than in the colder climate. This is because the embodied carbon stays the same throughout each region tested. However, the temperate region has less total carbon emission savings than the colder climate so the differences between operational carbon and embodied carbon are smaller. The cost savings are less significant as well. The return on investment timeline is just under the 25-year mark, and the savings are quite small. There are still positive savings, and carbon emissions are still being reduced; these savings will continue to grow throughout the life of the building.

Phoenix, AZ

The third climate will be a cooling-dominated, or hotter, climate in Phoenix, AZ. Phoenix is a hot desert climate, which does not have much of a winter and can have extreme cooling loads in the summer. The electric utility is 9.37 cents/kWh provided by the Salt River Project, the lowest of the three areas, and the location factor from RS-Means is 0.91, similar to that of Manhattan. This means the hot climate will have the lowest life cycle costs. The peak energy seasons differ significantly from the first two climates with a more even energy demand spread throughout the year. The eQuest energy outputs for Phoenix, AZ, are illustrated in Figures 10 and 11. The total values for embodied carbon, operational carbon, and associated costs are compiled in Table 14 and Figure 12 illustrates a comparison of embodied carbon to operational carbon.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Run 1.	1.44	1.10	1.07	1.15	1.45	1.81	1.93	2.07	1.62	1.36	0.98	1.30	17.28
Run 2.	2.05	1.65	1.20	1.24	1.65	2.19	2.37	2.49	1.88	1.42	1.09	1.95	21.19
Run 3.	2.23	1.84	1.30	1.29	1.72	2.34	2.57	2.65	1.95	1.45	1.18	2.12	22.64
Run 4.	2.34	1.97	1.40	1.36	1.79	2.44	2.69	2.75	2.02	1.50	1.28	2.24	23.77
Run 5.													

Figure 10: Electric Consumption for Phoenix

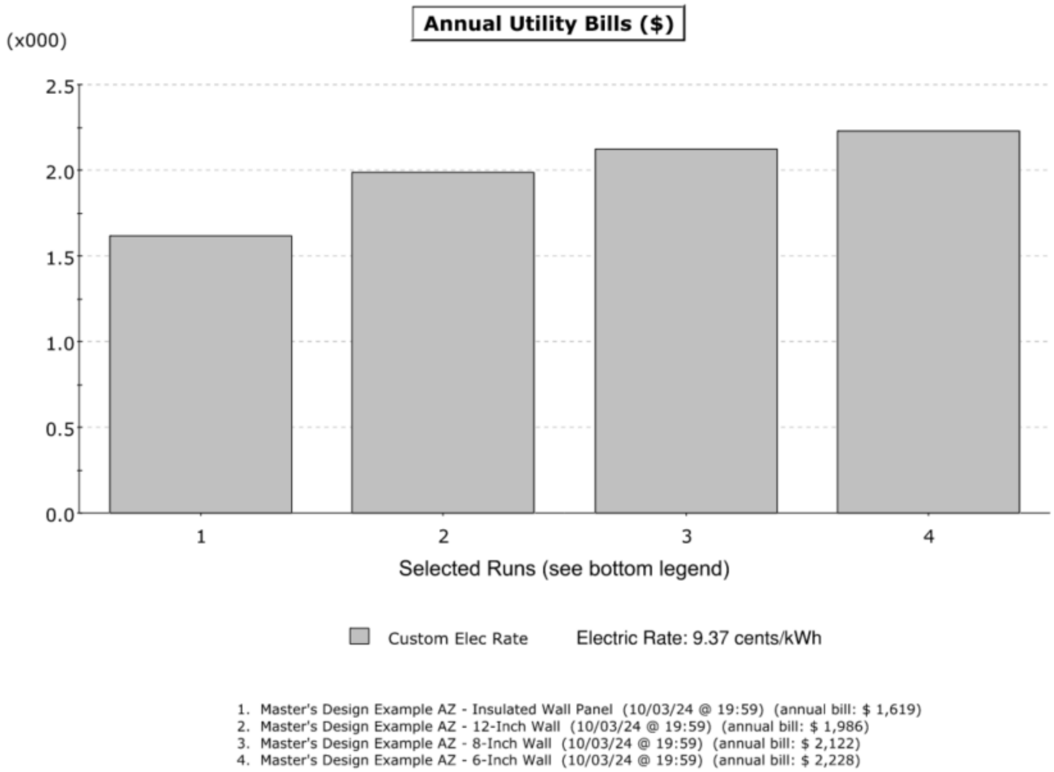
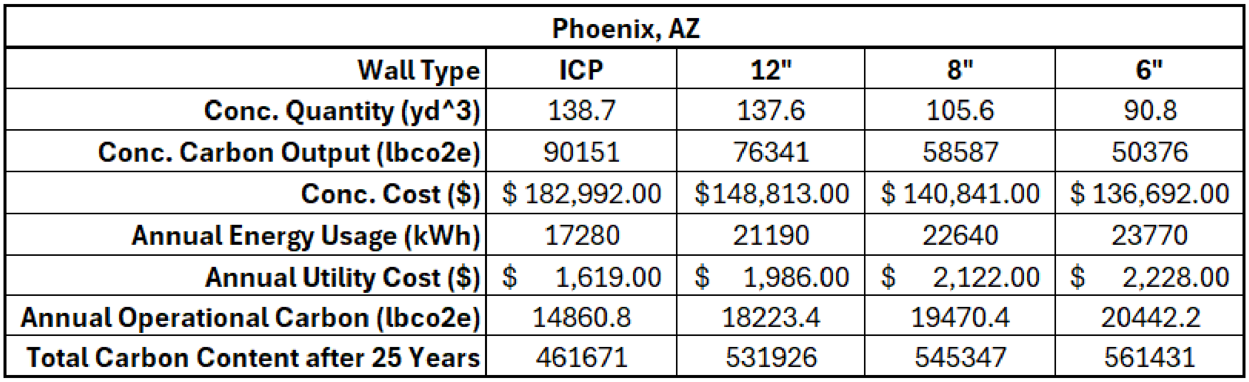


Figure 11: Annual Utility for Phoenix



Phoenix, AZ				
Wall Type	**ICP**	**12"**	**8"**	**6"**
Conc. Quantity (yd^3)	138.7	137.6	105.6	90.8
Conc. Carbon Output (lbco2e)	90151	76341	58587	50376
Conc. Cost ($)	$ 182,992.00	$148,813.00	$ 140,841.00	$ 136,692.00
Annual Energy Usage (kWh)	17280	21190	22640	23770
Annual Utility Cost ($)	$ 1,619.00	$ 1,986.00	$ 2,122.00	$ 2,228.00
Annual Operational Carbon (lbco2e)	14860.8	18223.4	19470.4	20442.2
Total Carbon Content after 25 Years	461671	531926	545347	561431

Table 14: Phoenix, AZ Results

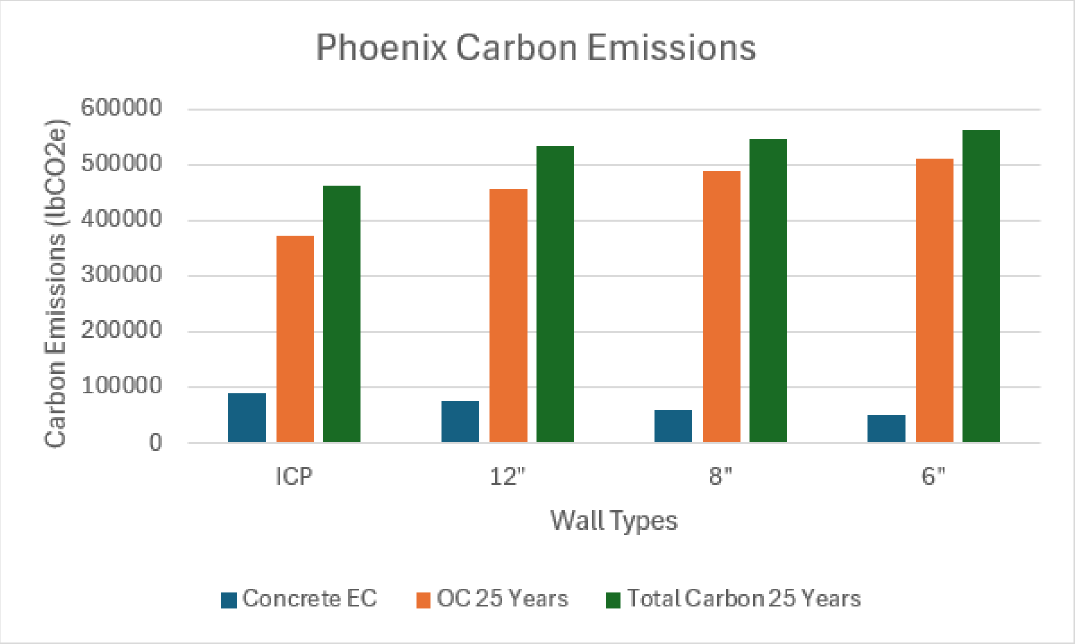
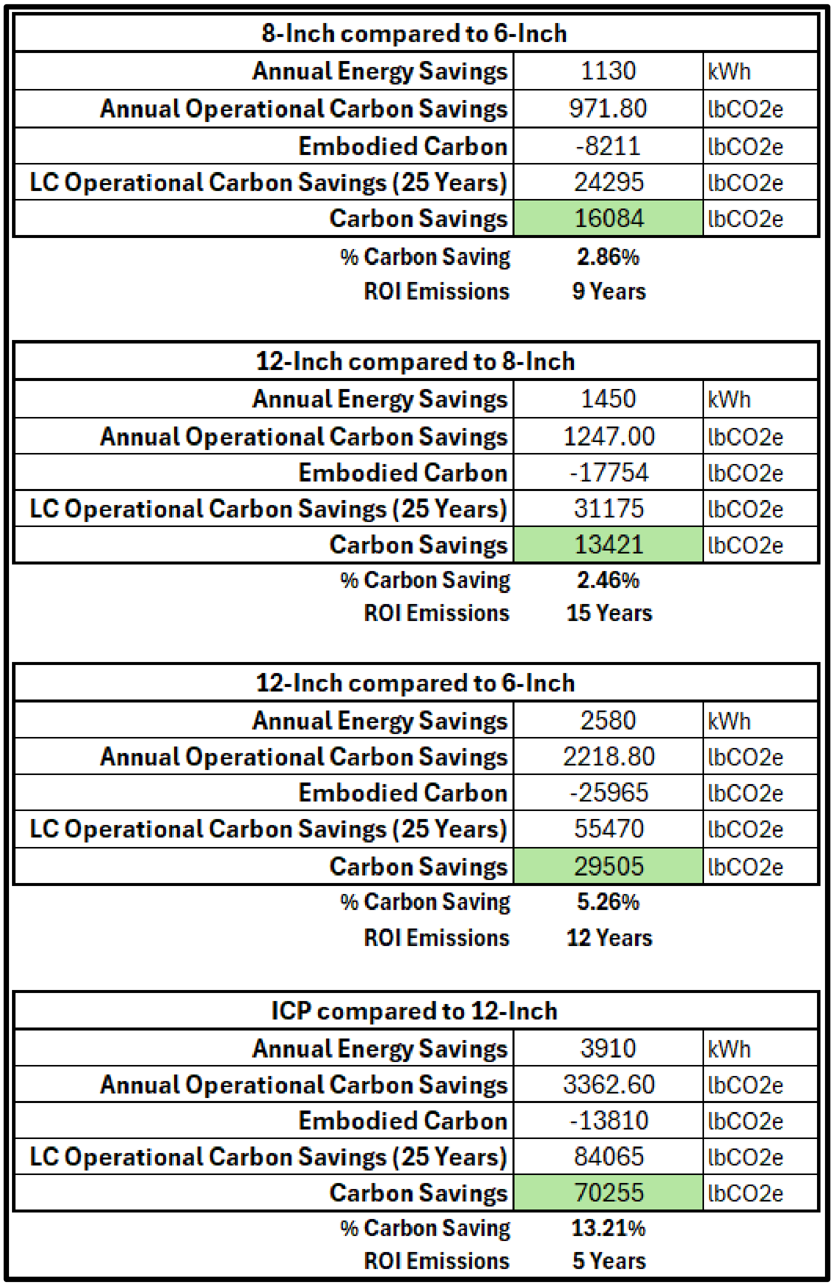


Figure 12: Carbon Emission Comparisons for Phoenix, AZ

Unlike temperate and cooler climates, the hotter climate experiences much higher cooling loads and has more peaks in the summer than in the winter. The energy demand is more evenly spread throughout the year, and the total energy usage per year is much less than in the other two colder climates. However, similarly, as the thickness of the walls increases and there is more thermal mass, the project's total carbon footprint decreases. The carbon content of the hotter climate is much lower than the others due to the lower energy demand. With lower energy demand and operational carbon content, the embodied carbon has more of an effect on the total carbon footprint, even though it is still reasonably small. The following tables 15, 16, and 17 will compare each wall type and the associated savings in carbon emissions and costs through the first 25 years caused by increased thermal mass.



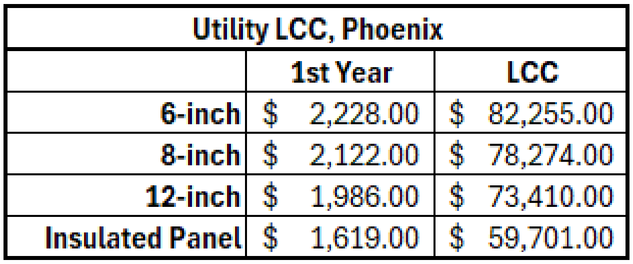
8-Inch compared to 6-Inch		
Annual Energy Savings	1130	kWh
Annual Operational Carbon Savings	971.80	lbCO2e
Embodied Carbon	-8211	lbCO2e
LC Operational Carbon Savings (25 Years)	24295	lbCO2e
Carbon Savings	16084	lbCO2e
% Carbon Saving	2.86%	
ROI Emissions	9 Years	

12-Inch compared to 8-Inch		
Annual Energy Savings	1450	kWh
Annual Operational Carbon Savings	1247.00	lbCO2e
Embodied Carbon	-17754	lbCO2e
LC Operational Carbon Savings (25 Years)	31175	lbCO2e
Carbon Savings	13421	lbCO2e
% Carbon Saving	2.46%	
ROI Emissions	15 Years	

12-Inch compared to 6-Inch		
Annual Energy Savings	2580	kWh
Annual Operational Carbon Savings	2218.80	lbCO2e
Embodied Carbon	-25965	lbCO2e
LC Operational Carbon Savings (25 Years)	55470	lbCO2e
Carbon Savings	29505	lbCO2e
% Carbon Saving	5.26%	
ROI Emissions	12 Years	

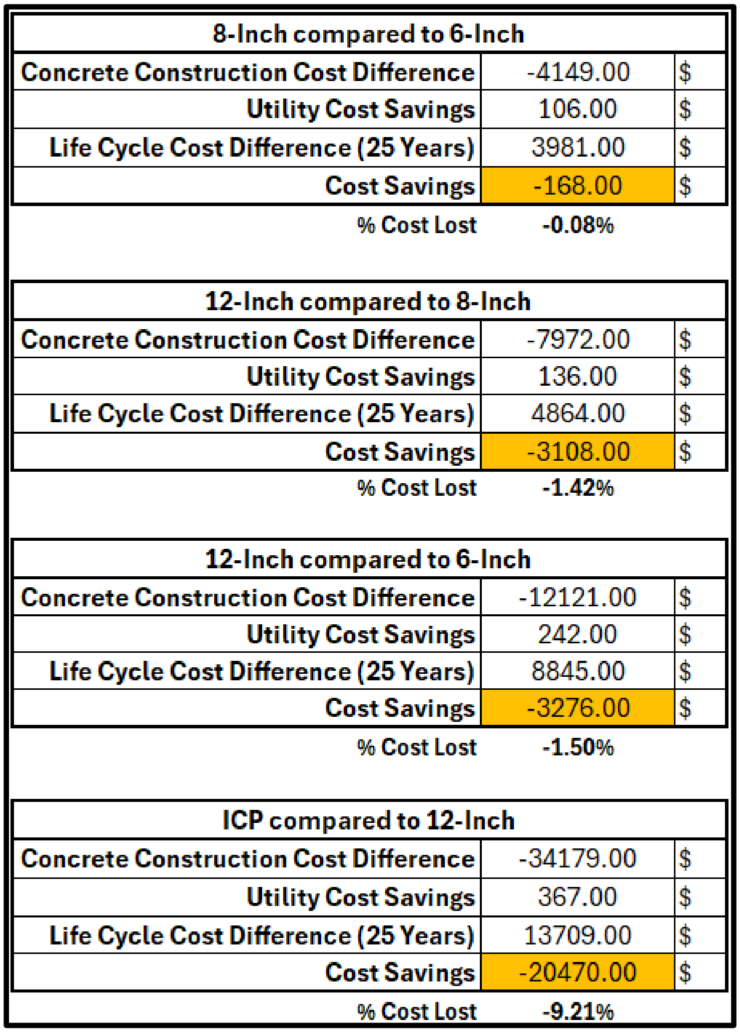
ICP compared to 12-Inch		
Annual Energy Savings	3910	kWh
Annual Operational Carbon Savings	3362.60	lbCO2e
Embodied Carbon	-13810	lbCO2e
LC Operational Carbon Savings (25 Years)	84065	lbCO2e
Carbon Savings	70255	lbCO2e
% Carbon Saving	13.21%	
ROI Emissions	5 Years	

Table 15: Energy and carbon savings between wall types for Phoenix: (negative entries indicate increased carbon)



Utility LCC, Phoenix		
	1st Year	LCC
6-inch	$ 2,228.00	$ 82,255.00
8-inch	$ 2,122.00	$ 78,274.00
12-inch	$ 1,986.00	$ 73,410.00
Insulated Panel	$ 1,619.00	$ 59,701.00

Table 16: Utility Life Cycle Cost Analysis for Phoenix



8-Inch compared to 6-Inch		
Concrete Construction Cost Difference	-4149.00	$
Utility Cost Savings	106.00	$
Life Cycle Cost Difference (25 Years)	3981.00	$
Cost Savings	-168.00	$
% Cost Lost	-0.08%	

12-Inch compared to 8-Inch		
Concrete Construction Cost Difference	-7972.00	$
Utility Cost Savings	136.00	$
Life Cycle Cost Difference (25 Years)	4864.00	$
Cost Savings	-3108.00	$
% Cost Lost	-1.42%	

12-Inch compared to 6-Inch		
Concrete Construction Cost Difference	-12121.00	$
Utility Cost Savings	242.00	$
Life Cycle Cost Difference (25 Years)	8845.00	$
Cost Savings	-3276.00	$
% Cost Lost	-1.50%	

ICP compared to 12-Inch		
Concrete Construction Cost Difference	-34179.00	$
Utility Cost Savings	367.00	$
Life Cycle Cost Difference (25 Years)	13709.00	$
Cost Savings	-20470.00	$
% Cost Lost	-9.21%	

Table 17: Cost savings between wall types for Phoenix: (negative entries indicate increased costs)

The warmer climate sees a similar percent savings increase as the thermal mass increases, which is also an effective climate for increasing thermal mass from a carbon emissions standpoint. The 12-inch wall has 5.26% less carbon emission content than the 6-inch wall. The return on investment period is the largest for this climate, between 9-15 years for the concrete-only walls and 5 years for the ICP. These are still relatively low periods in terms of the life of the building, and the savings will increase. The ICP is still effective from a carbon standpoint for this region but less effective than the other regions. The hot climate building sees the least carbon savings in pounds per CO2 because of the lower energy demand. Increasing thermal mass is still effective from a sustainability standpoint. However, due to the lower utility cost per kilowatt hour and lower energy demand, there are no cost savings from the initial concrete costs in the 25-year life cycle. For the concrete-only walls, the cost lost is low, but for the ICP, the cost difference is significant. The differences will continue to shrink throughout the life of the building. It becomes less cost-effective in areas with lower utility rates and lower energy demands because the differences in embodied carbon and initial costs become more significant. The insulated panel is less effective in this climate than the others, illustrating that adding insulation is more beneficial in colder climates.

End Result

With increased thermal mass, all three climate regions saw increased thermal efficiency through operational carbon savings over the 25 years. The more significant the increase in thermal mass, the more substantial the reduction in carbon emissions. In colder and temperate climates, the thermal mass benefit is most seen in the winter months, while in the hotter climates, it is more evenly effective throughout the year. The colder climate of Minneapolis saw the most significant energy usage and operational carbon values, while the hotter climate of Phoenix saw the lowest energy usage and operational carbon values. The walls in the hotter climate have the lowest carbon footprints in pounds of CO2, while the colder climate sees the most carbon emission savings when the thermal mass is increased. In terms of percent savings through increasing thermal mass, the three climates have similar differences from a carbon footprint standpoint between thermal mass intervals. Climates with colder weather are the most effective for using thermal mass to reduce carbon emissions. Carbon emission savings can be seen within 7-9 years just from increasing the thickness of the concrete walls, and these effects are amplified when insulation is added.

The results show that increased thermal mass design can result in cost savings. At the 25-year life cycle, increasing thermal mass for colder and temperate climates results in small cost savings, which will continue to increase with time. In colder climates, the additional thermal efficiency from increased thermal mass will result in a return on investment for the increased initial costs in 17-18 years. In warmer climates, using more thermal mass is not as cost-effective due to the lower energy demand and low utility costs, which means spending more money upfront will not be paid back in the same period; more time will be needed. This conclusion is based on the comparison between wall types for a region. Overall, the warmer climate has a lower utility rate and energy demands, so the utility life cycle for cost and CO2 emissions is much lower than the other regions. The best results are from the insulated concrete panel wall, it has a significant increase in carbon emission savings and cost savings for the colder climates. Significant carbon emission reductions exist in every climate, and cost savings exist for colder and temperate climates. Combining high thermal mass and insulation is the most thermally efficient design.

Chapter 7: Conclusion and Recommendations

The primary goal of sustainability is to reduce energy consumption and greenhouse gas emissions, which are critical to combating climate change. Concrete is a prominently used building material, but its production is both resource and energy-intensive, resulting in it being a major cause of carbon emissions. With concrete's dense composition and material properties, it has a very high thermal mass. Thermal mass refers to the ability of a material to absorb, store, and release heat energy. Using thermal mass presents a sustainable strategy to reduce operational carbon emissions in buildings through moderating indoor temperature fluctuations. For thermal mass to be effective in building energy reduction, it needs to be distributed and designed properly based on the climate region of the project. Adding thickness to the walls and floors will increase thermal storage and decrease the concrete's thermal conductivity, creating a more efficient design. Thermal mass performs well in temperatures above the comfort zone during the day and below at night, a large temperature variation. The climate will decide whether to lower conductivity and/or increase density and specific heat capacity. Finding the optimized relation between these two properties for a given climate will lead to the most thermally efficient design. A case study investigated the effects of increased thermal mass in concrete walls versus the thermal and energy performance of buildings in different geographical locations throughout the United States. The results indicate that thermal mass can positively affect a building's energy efficiency and carbon footprint for cold, temperate, and hot climate regions. Increasing the thickness of the concrete wall results in increased concrete quantity, embodied carbon, and concrete initial costs while decreasing annual energy usage, utility costs, and operational carbon. As the thickness of the walls increases and there is more thermal mass, the total carbon footprint of the project decreases—the more significant the increase in thermal mass, the more operational carbon savings and cost savings. In colder and temperate climates, the thermal mass benefit is most seen in the summer months, while in the hotter climates, it is most effective in the winter months. The colder climate of Minneapolis saw the most significant energy usage and operational carbon values, while the hotter climate of Phoenix saw the lowest energy usage and operational carbon values. The colder climate sees the most significant carbon savings increase as thermal mass increases, meaning it is the most effective climate for increasing thermal mass from a carbon emissions standpoint. Implementing sustainable systems usually comes with higher upfront costs. Still, the results illustrate that the long-term benefits, including energy savings and reduced operating costs, can outweigh the initial investment and create cost savings for the colder and temperate climates. Increasing thermal mass is less cost-effective due to lower energy demands in warmer climates. Other cost savings can be found in government incentives and tax credits rewarded for green building practices.

As the industry continues to evolve towards more sustainable practices, the role of concrete's thermal mass in reducing carbon emissions and enhancing energy efficiency will undoubtedly gain greater recognition. Future research should explore innovative ways to maximize these benefits through optimizing concrete properties and exploring new design approaches. ASHRAE Standard 90.1 now acknowledges the thermal mass benefits of concrete walls by specifying lower minimum R-values and higher maximum U-factors for mass concrete construction. Engineers aim to implement best practices and consider all design options for sustainable concrete design, and the information in this report will help them continue to do so.

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Appendix A - Case Study Calculations

The following pages will present the calculations for the case study structure foundations and construction costs.

Thermal Mass Design Example

Design Constants:

Structural Layout: 2-story frame, 30'x30' bay, 10' floor height

Concrete Composition: Normal Weight Concrete: Density $\gamma := 150\ \boldsymbol{pcf}$

Compressive Strength: $f'c := 4000\ \boldsymbol{psi}$

Composite Floor Slab: 4" Slab on 3" Metal Deck, 69 PSF

Slab on Grade: 6" Floor Slab on grade

Loading:

Floor Live Load: $L_f := 100\ \boldsymbol{psf}$

Floor Dead Load: $d := 25\ \boldsymbol{psf}$

$d_{sw} := 69\ \boldsymbol{psf}$ Slab Self-Weight (Vulcraft Manual)

$D_f := 94\ \boldsymbol{psf}$

Unfactored Load on Floor: $w_f := D_f + L_f = 194\ \boldsymbol{psf}$

Factored Load on Floor: $w_F := 1.2 \cdot D_f + 1.6 \cdot L_f = 272.8\ \boldsymbol{psf}$

Roof Live Load: $L_r := 20\ \boldsymbol{psf}$

Roof Dead Load: $D_r := 20\ \boldsymbol{psf}$

Unfactored Load on Roof: $w_r := D_r + L_r = 40\ \boldsymbol{psf}$

Factored Load on Roof: $w_R := 1.2 \cdot D_r + 1.6 \cdot L_r = 56\ \boldsymbol{psf}$

Design 1 - 6" Wall Design:

Wall Thickness: $t_6 := 6\ in$

Wall Area: $A_w := 30\ ft \cdot 10\ ft = 300\ ft^2$

Total Concrete Wall Area (two floors): $A := (4 \cdot A_w) \cdot 2 = 2400\ ft^2$

Volume of Walls Concrete: $V_{walls} := A \cdot t_6 = 1200\ ft^3$

Loading on Columns for Foundations:

Height of Walls: $h_w := 10\ ft$

Weight of Walls: $w_w := \gamma \cdot h_w \cdot t_6 = 750\ plf$

Length of Walls on Column: $l_w := 30\ ft$ 15 feet from each corner

Column Load from wall on second level: $P_w := w_w \cdot l_w = 22.5\ kip$

Tributary Area: $t_a := 15\ ft \cdot 15\ ft = 225\ ft^2$

Unfactored Load on Columns: $P_{col.unf} := \left(\left(w_f + w_r\right) \cdot t_a\right) + P_w = 75.15\ kip$

Grade Beam Design:

Load on Grade Beam = Self Weight of First Floor Wall and Self Weight of Beam

Wall Thickness: $t_6 := 6\ in$

Wall Height: $h_w := 10\ ft$

Length of Wall: $l_w := 30\ ft$

Self Weight of Wall: $w_w := \gamma \cdot t_6 \cdot h_w = 0.75\ \frac{kip}{ft}$

Beam Dimensions:

Assume Height: $h := 16\ in$

Depth of Steel: $d := 12.5\ in$

Width of Beam: $b := 12\ in$

Self Weight of Beam: $w_b := \gamma \cdot h \cdot b = 0.2\ \frac{kip}{ft}$

$f_y := 60000\ psi$ $f'c := 4000\ psi$ $\beta := .85$ $l_b := 30\ ft$

Factored Load: $W_u := 1.2 \cdot \left(w_w + w_b\right) = 1.14\ \frac{kip}{ft}$

Design Moment: $M := \frac{W_u \cdot {l_w}^2}{8} = 128.25\ kip \cdot ft$

$A_s = \frac{M}{4 \cdot d} = \frac{128.25}{4 \cdot 12} = 2.672\ in^2$ Use (3) #9 Rebar

$A_s := 3.0\ in^2$

$a := \frac{A_s \cdot f_y}{0.85 \cdot f'c \cdot b} = 4.41\ in$

$\phi M_n := 0.9 \cdot A_s \cdot f_y \cdot \left(d - \frac{a}{2}\right) = 139\ kip \cdot ft$ $O.K.$

$c := \frac{a}{\beta} = 5.19\ in$

$\varepsilon_T := \frac{d - c}{c} \cdot 0.003 = 0.0042$ $\varepsilon_T \le 0.005$ Good

Reactions From Grade Beam to Spread Footing:

Unfactored Load: $w_{un} := w_b + w_w = 0.95\ \frac{kip}{ft}$

$P_{un} := w_{un} \cdot l_w = 28.5\ kip$

Unfactored Reaction: $R_{un} := \frac{P_{un}}{2} = 14.25\ kip$

Factored Load: $W_u = 1.14\ \frac{kip}{ft}$

$P_{fact} := W_u \cdot l_w = 34.2\ kip$

Factored Reaction: $R_u := \frac{P_{fact}}{2} = 17.1\ kip$

Unfactored Load For Foundations: $P := P_{col.unf} + R_{un} = 89.4\ kip$

Foundation Design:

Spread Footing under Columns

1. Size of Footing

Soil Bearing Capacity: $p := 2000\ psf$ (Assumed Value)

Required Minimum Size: $A_{req} := \frac{P}{p} = 44.7\ ft^2$

Assume square, side dimension: $a := \sqrt{A_{req}} = 6.686\ ft$

Will use 8' x 8'

$a := 8\ ft$ $A := a^2 = 64\ ft^2$

2. Thickness of Footing

$f'c := 4000\ psi$ normal weight concrete $\lambda := 1$

One-way shear: $b_w := a = 96\ in$

Factored Load on Columns: $P_u := \left(\left(w_F + w_R\right) \cdot t_a\right) + \left(1.2 \cdot P_w\right) + R_u = 118.08\ kip$

$$q_u := \frac{P_u}{A} = 1.845\ \mathbf{ksf}$$

Assume a 16" x 16" column base plate, $b_{bp} := 16\ \mathbf{in}$ and a W10 Column $d_c := 10\ \mathbf{in}$

Critical Section: $c := \frac{b_{bp} + d_c}{4} = 6.5\ \mathbf{in}$

Cantilever Length: $l := \frac{a}{2} - c = 41.5\ \mathbf{in}$

Footing Minimum Thickness

One-Way Shear $V_u := q_u \cdot b_w \cdot l = 51.045\ \mathbf{kip}$

Assume $\rho_w := 0.003$ $\lambda_s := 1$ $\phi := 0.75$ $V_c = 8 \cdot \lambda_s \cdot \lambda \cdot (\rho_w)^{\frac{1}{3}} \cdot \sqrt{f'c} \cdot b_w \cdot d > V_u$

Minimum d: $$d_{req} := \frac{V_u}{\phi \cdot 8 \cdot \lambda_s \cdot \lambda \cdot (\rho_w)^{\frac{1}{3}} \cdot \sqrt{\frac{f'c}{\mathbf{psi}}} \cdot \mathbf{psi} \cdot b_w} = 9.715\ \mathbf{in}$$

From ACI 318-19 Table 20.5.1.3.1, concrete cover needs to be $cover := 3\ \mathbf{in}$

Assume #9 rebar, $d_r := 1.128\ \mathbf{in}$

Required Total Thickness: $h_{req} := d_{req} + cover + d_r + \frac{d_r}{2} = 14.407\ \mathbf{in}$

$$\therefore\ h := 16\ \mathbf{in}$$

$$d := h - cover - d_r - \frac{d_r}{2} = 11.308\ \mathbf{in}$$

$$V_c := 8 \cdot \lambda_s \cdot \lambda \cdot (\rho_w)^{\frac{1}{3}} \cdot \sqrt{\frac{f'c}{\mathbf{psi}}} \cdot \mathbf{psi} \cdot b_w \cdot d = 79.217\ \mathbf{kip}$$

$\phi \cdot V_c = 59.413\ \mathbf{kip}$ $\phi V_c > V_u$ $V_u = 51.045\ \mathbf{kip}$ OK

Concrete Quantity from Foundations:

Spread Footings For Columns (4):

Size: $w_{f1} := 8\ ft$ $l_{f1} := 8\ ft$ $t_{f1} := 16\ in$

Total Volume: $V_F := \left(w_{f1} \cdot l_{f1} \cdot t_{f1}\right) \cdot 4 = 341.333\ ft^3$

Grade Beams (4):

Size: $h := 16\ in$ $b := 12\ in$ $l := 30\ ft$

Total Volume: $V_{gb} := (h \cdot b \cdot l) \cdot 4 = 160\ ft^3$

Slab Concrete Volume:

Slab Thickness: $t_s := 4\ in$ Slab on Grade thickness: $t_{sg} := 6\ in$

Floor Area: $A_f := 30\ ft \cdot 30\ ft = 900\ ft^2$

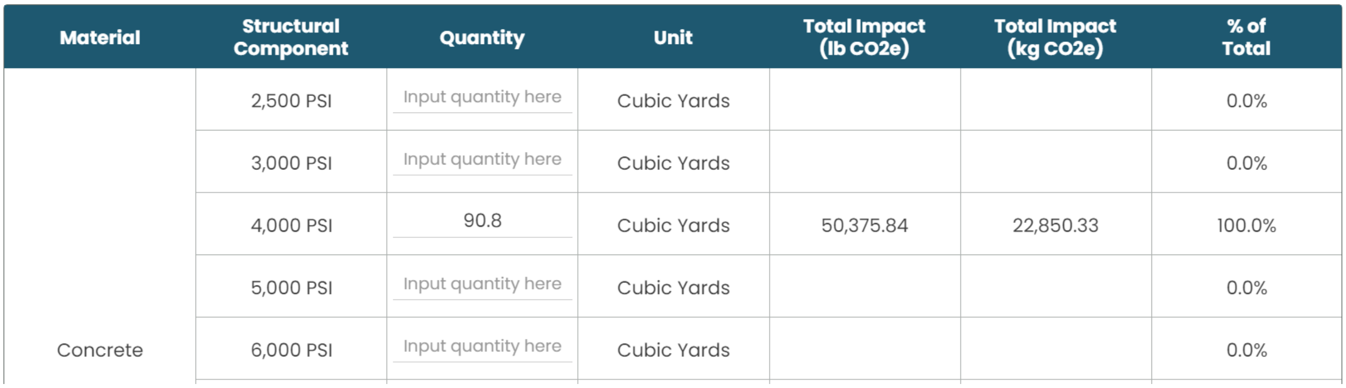
Slab Volume: $V_{slabs} := \left(A_f \cdot t_s\right) + \left(A_f \cdot t_{sg}\right) = 750\ ft^3$

Total Volume of Concrete in Structure:

$$V_{total} := V_{walls} + V_{slabs} + V_F + V_{gb} = 2451.333\ ft^3 \qquad V_{total} = 90.8\ yd^3$$

Carbon Content: $CC_6 = 50376\ lbco2e$ (ECOM SE2050 Carbon Calculator Output)

ECOM SE 2050 Output:



Material	Structural Component	Quantity	Unit	Total Impact (lb CO2e)	Total Impact (kg CO2e)	% of Total
Concrete	2,500 PSI	Input quantity here	Cubic Yards			0.0%
	3,000 PSI	Input quantity here	Cubic Yards			0.0%
	4,000 PSI	90.8	Cubic Yards	50,375.84	22,850.33	100.0%
	5,000 PSI	Input quantity here	Cubic Yards			0.0%
	6,000 PSI	Input quantity here	Cubic Yards			0.0%

Thermal Mass Design Example

Design Constants:

Structural Layout: 2-story frame, 30'x30' bay, 10' floor height

Concrete Composition: Normal Weight Concrete: Density $\gamma := 150\ pcf$

Compressive Strength: $f'c := 4000\ psi$

Composite Floor Slab: 4" Slab on 3" Metal Deck, 69 PSF

Slab on Grade: 6" Floor Slab on grade

Loading:

Floor Live Load: $L_f := 100\ psf$

Floor Dead Load: $d := 25\ psf$

$d_{sw} := 69\ psf$ Slab Self-Weight (Vulcraft Manual)

$D_f := 94\ psf$

Unfactored Load on Floor: $w_f := D_f + L_f = 194\ psf$

Factored Load on Floor: $w_F := 1.2 \cdot D_f + 1.6 \cdot L_f = 272.8\ psf$

Roof Live Load: $L_r := 20\ psf$

Roof Dead Load: $D_r := 20\ psf$

Unfactored Load on Roof: $w_r := D_r + L_r = 40\ psf$

Factored Load on Roof: $w_R := 1.2 \cdot D_r + 1.6 \cdot L_r = 56\ psf$

Design 2 - 8" Wall Design:

Wall Thickness: $t_8 := 8\ in$

Wall Area: $A_w := 30\ ft \cdot 10\ ft = 300\ ft^2$

Total Concrete Wall Area (two floors): $A := \left(4 \cdot A_w\right) \cdot 2 = 2400\ ft^2$

Volume of Walls Concrete: $V_{walls} := A \cdot t_8 = 1600\ ft^3$

Loading on Columns for Foundations:

Height of Walls: $h_w := 10\ ft$

Weight of Walls: $w_w := \gamma \cdot h_w \cdot t_8 = 1000\ plf$

Length of Walls on Column: $l_w := 30\ ft$ 15 feet from each corner

Column Load from wall on second level: $P_w := w_w \cdot l_w = 30\ kip$

Tributary Area: $t_a := 15\ ft \cdot 15\ ft = 225\ ft^2$

Unfactored Load on Columns: $P_{col.unf} := \left(\left(w_f + w_r\right) \cdot t_a\right) + P_w = 82.65\ kip$

Grade Beam Design:

Load on Grade Beam = Self Weight of First Floor Wall and Self Weight of Beam

Wall Thickness: $t_8 := 8\ in$

Wall Height: $h_w := 10\ ft$

Length of Wall: $l_w := 30\ ft$

Self Weight of Wall: $w_w := \gamma \cdot t_8 \cdot h_w = 1\ \frac{kip}{ft}$

Beam Dimensions:

Assume Height: $h := 16\ \mathbf{in}$

Depth of Steel: $d := 12.5\ \mathbf{in}$

Width of Beam: $b := 12\ \mathbf{in}$

Self Weight of Beam: $w_b := \gamma \cdot h \cdot b = 0.2\ \frac{\mathbf{kip}}{\mathbf{ft}}$

$f_y := 60000\ \mathbf{psi}$ $\quad f'c := 4000\ \mathbf{psi}$ $\quad \beta := .85$ $\quad l_b := 30\ \mathbf{ft}$

Factored Load: $W_u := 1.2 \cdot \left(w_w + w_b\right) = 1.44\ \frac{\mathbf{kip}}{\mathbf{ft}}$

Design Moment: $M := \frac{W_u \cdot {l_w}^2}{8} = 162\ \mathbf{kip} \cdot \mathbf{ft}$

$A_s = \frac{M}{4 \cdot d} = \frac{162}{4 \cdot 12} = 3.375\ in^2$ Use (4) #9 Rebar

$A_s := 4.0\ \mathbf{in}^2$

$a := \frac{A_s \cdot f_y}{0.85 \cdot f'c \cdot b} = 5.88\ \mathbf{in}$

$\phi M_n := 0.9 \cdot A_s \cdot f_y \cdot \left(d - \frac{a}{2}\right) = 172.1\ \mathbf{kip} \cdot \mathbf{ft}$ $\quad O.K.$

$c := \frac{a}{\beta} = 6.92\ \mathbf{in}$

$\varepsilon_T := \frac{d - c}{c} \cdot 0.003 = 0.0024$ $\quad \varepsilon_T \le 0.005$ Good

Reactions From Grade Beam to Spread Footing:

Unfactored Load: $w_{un} := w_b + w_w = 1.2\ \frac{kip}{ft}$

$P_{un} := w_{un} \cdot l_w = 36\ kip$

Unfactored Reaction: $R_{un} := \frac{P_{un}}{2} = 18\ kip$

Factored Load: $W_u = 1.44\ \frac{kip}{ft}$

$P_{fact} := W_u \cdot l_w = 43.2\ kip$

Factored Reaction: $R_u := \frac{P_{fact}}{2} = 21.6\ kip$

Unfactored Load For Foundations: $P := P_{col.unf} + R_{un} = 100.65\ kip$

Foundation Design:

Spread Footing under Columns

1. Size of Footing

Soil Bearing Capacity: $p := 2000\ psf$ (Assumed Value)

Required Minimum Size: $A_{req} := \frac{P}{p} = 50.325\ ft^2$

Assume square, side dimension: $a := \sqrt{A_{req}} = 7.094\ ft$

Will use 8' x 8'

$a := 8\ ft$ $A := a^2 = 64\ ft^2$

2. Thickness of Footing

$f'c := 4000\ psi$ normal weight concrete $\lambda := 1$

One-way shear: $b_w := a = 96\ in$

Factored Load on Columns: $P_u := \left(\left(w_F + w_R\right) \cdot t_a\right) + \left(1.2 \cdot P_w\right) + R_u = 131.58\ kip$

$$q_u := \frac{P_u}{A} = 2.056\ \textit{ksf}$$

Assume a 16" x 16" column base plate, $b_{bp} := 16\ \textit{in}$ and a W10 Column $d_c := 10\ \textit{in}$

Critical Section: $c := \frac{b_{bp} + d_c}{4} = 6.5\ \textit{in}$

Cantilever Length: $l := \frac{a}{2} - c = 41.5\ \textit{in}$

Footing Minimum Thickness

One-Way Shear $V_u := q_u \cdot b_w \cdot l = 56.881\ \textit{kip}$

Assume $\rho_w := 0.003$ $\lambda_s := 1$ $\phi := 0.75$ $V_c = 8 \cdot \lambda_s \cdot \lambda \cdot (\rho_w)^{\frac{1}{3}} \cdot \sqrt{f'c} \cdot b_w \cdot d > V_u$

Minimum d: $d_{req} := \dfrac{V_u}{\phi \cdot 8 \cdot \lambda_s \cdot \lambda \cdot (\rho_w)^{\frac{1}{3}} \cdot \sqrt{\dfrac{f'c}{\textit{psi}}} \cdot \textit{psi} \cdot b_w} = 10.826\ \textit{in}$

From ACI 318-19 Table 20.5.1.3.1, concrete cover needs to be $cover := 3\ \textit{in}$

Assume #9 rebar, $d_r := 1.128\ \textit{in}$

Required Total Thickness: $h_{req} := d_{req} + cover + d_r + \frac{d_r}{2} = 15.518\ \textit{in}$

$$\therefore\ h := 16\ \textit{in}$$

$$d := h - cover - d_r - \frac{d_r}{2} = 11.308\ \textit{in}$$

$$V_c := 8 \cdot \lambda_s \cdot \lambda \cdot (\rho_w)^{\frac{1}{3}} \cdot \sqrt{\frac{f'c}{\textit{psi}}} \cdot \textit{psi} \cdot b_w \cdot d = 79.217\ \textit{kip}$$

$\phi \cdot V_c = 59.413\ \textit{kip}$ $\phi V_c > V_u$ $V_u = 56.881\ \textit{kip}$ OK

Concrete Quantity from Foundations:

Spread Footings For Columns (4):

Size: $w_{f1} := 8\ ft$ $l_{f1} := 8\ ft$ $t_{f1} := 16\ in$

Total Volume: $V_F := (w_{f1} \cdot l_{f1} \cdot t_{f1}) \cdot 4 = 341.333\ ft^3$

Grade Beams (4):

Size: $h := 16\ in$ $b := 12\ in$ $l := 30\ ft$

Total Volume: $V_{gb} := (h \cdot b \cdot l) \cdot 4 = 160\ ft^3$

Slab Concrete Volume:

Slab Thickness: $t_s := 4\ in$ Slab on Grade thickness: $t_{sg} := 6\ in$

Floor Area: $A_f := 30\ ft \cdot 30\ ft = 900\ ft^2$

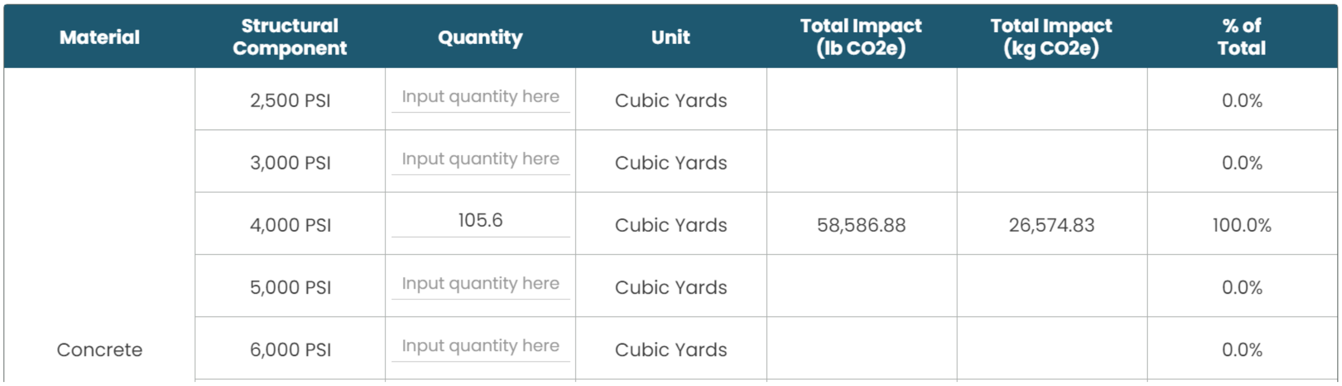
Slab Volume: $V_{slabs} := (A_f \cdot t_s) + (A_f \cdot t_{sg}) = 750\ ft^3$

Total Volume of Concrete in Structure:

$$V_{total} := V_{walls} + V_{slabs} + V_F + V_{gb} = 2851.333\ ft^3 \qquad V_{total} = 105.6\ yd^3$$

Carbon Content: $CC_8 = 58587\ lbco2e$ (ECOM SE2050 Carbon Calculator Output)

ECOM SE 2050 Output:



Material	Structural Component	Quantity	Unit	Total Impact (lb CO2e)	Total Impact (kg CO2e)	% of Total
Concrete	2,500 PSI	Input quantity here	Cubic Yards			0.0%
	3,000 PSI	Input quantity here	Cubic Yards			0.0%
	4,000 PSI	105.6	Cubic Yards	58,586.88	26,574.83	100.0%
	5,000 PSI	Input quantity here	Cubic Yards			0.0%
	6,000 PSI	Input quantity here	Cubic Yards			0.0%

Thermal Mass Design Example

Design Constants:

Structural Layout: 2-story frame, 30'x30' bay, 10' floor height

Concrete Composition: Normal Weight Concrete: Density $\gamma := 150\ pcf$

Compressive Strength: $f'c := 4000\ psi$

Composite Floor Slab: 4" Slab on 3" Metal Deck, 69 PSF

Slab on Grade: 6" Floor Slab on grade

Loading:

Floor Live Load: $L_f := 100\ psf$

Floor Dead Load: $d := 25\ psf$

$d_{sw} := 69\ psf$ Slab Self-Weight (Vulcraft Manual)

$D_f := 94\ psf$

Unfactored Load on Floor: $w_f := D_f + L_f = 194\ psf$

Factored Load on Floor: $w_F := 1.2 \cdot D_f + 1.6 \cdot L_f = 272.8\ psf$

Roof Live Load: $L_r := 20\ psf$

Roof Dead Load: $D_r := 20\ psf$

Unfactored Load on Roof: $w_r := D_r + L_r = 40\ psf$

Factored Load on Roof: $w_R := 1.2 \cdot D_r + 1.6 \cdot L_r = 56\ psf$

Design 3 - 12" Wall Design:

Wall Thickness: $t_{12} := 12\ in$

Wall Area: $A_w := 30\ ft \cdot 10\ ft = 300\ ft^2$

Total Concrete Wall Area (two floors): $A := (4 \cdot A_w) \cdot 2 = 2400\ ft^2$

Volume of Walls Concrete: $V_{walls} := A \cdot t_{12} = 2400\ ft^3$

Loading on Columns for Foundations:

Height of Walls: $h_w := 10\ ft$

Weight of Walls: $w_w := \gamma \cdot h_w \cdot t_{12} = 1500\ plf$

Length of Walls on Column: $l_w := 30\ ft$ 15 feet from each corner

Column Load from wall on second level: $P_w := w_w \cdot l_w = 45\ kip$

Tributary Area: $t_a := 15\ ft \cdot 15\ ft = 225\ ft^2$

Unfactored Load on Columns: $P_{col.unf} := \left(\left(w_f + w_r\right) \cdot t_a\right) + P_w = 97.65\ kip$

Grade Beam Design:

Load on Grade Beam = Self Weight of First Floor Wall and Self Weight of Beam

Wall Thickness: $t_{12} := 12\ in$

Wall Height: $h_w := 10\ ft$

Length of Wall: $l_w := 30\ ft$

Self Weight of Wall: $w_w := \gamma \cdot t_{12} \cdot h_w = 1.5\ \frac{kip}{ft}$

Beam Dimensions:

Assume Height: $h := 18\ in$

Depth of Steel: $d := 14.5\ in$

Width of Beam: $b := 12\ in$

Self Weight of Beam: $w_b := \gamma \cdot h \cdot b = 0.225\ \frac{kip}{ft}$

$f_y := 60000\ psi$ $f'c := 4000\ psi$ $\beta := .85$ $l_b := 30\ ft$

Factored Load: $W_u := 1.2 \cdot (w_w + w_b) = 2.07\ \frac{kip}{ft}$

Design Moment: $M := \frac{W_u \cdot {l_w}^2}{8} = 232.875\ kip \cdot ft$

$A_s = \frac{M}{4 \cdot d} = \frac{232.875}{4 \cdot 12} = 4.852\ in^2$ Use (5) #9 Rebar

$A_s := 5.0\ in^2$

$$a := \frac{A_s \cdot f_y}{0.85 \cdot f'c \cdot b} = 7.35\ in$$

$$\phi M_n := 0.9 \cdot A_s \cdot f_y \cdot \left(d - \frac{a}{2}\right) = 243.5\ kip \cdot ft \qquad O.K.$$

$$c := \frac{a}{\beta} = 8.651\ in$$

$$\varepsilon_T := \frac{d-c}{c} \cdot 0.003 = 0.002 \qquad \varepsilon_T \le 0.005$$ Good

Reactions From Grade Beam to Spread Footing:

Unfactored Load: $w_{un} := w_b + w_w = 1.725\ \frac{kip}{ft}$

$P_{un} := w_{un} \cdot l_w = 51.75\ kip$

Unfactored Reaction: $R_{un} := \frac{P_{un}}{2} = 25.875\ kip$

Factored Load: $W_u = 2.07\ \frac{kip}{ft}$

$P_{fact} := W_u \cdot l_w = 62.1\ kip$

Factored Reaction: $R_u := \frac{P_{fact}}{2} = 31.05\ kip$

Unfactored Load For Foundations: $P := P_{col.unf} + R_{un} = 123.525\ kip$

Foundation Design:

Spread Footing under Columns

1. Size of Footing

Soil Bearing Capacity: $p := 2000\ psf$ (Assumed Value)

Required Minimum Size: $A_{req} := \frac{P}{p} = 61.763\ ft^2$

Assume square, side dimension: $a := \sqrt{A_{req}} = 7.859\ ft$

Will use 8' x 8'

$a := 8\ ft$ $A := a^2 = 64\ ft^2$

2. Thickness of Footing

$f'c := 4000\ psi$ normal weight concrete $\lambda := 1$

One-way shear: $b_w := a = 96\ in$

Factored Load on Columns: $P_u := \left(\left(w_F + w_R\right) \cdot t_a\right) + \left(1.2 \cdot P_w\right) + R_u = 159.03\ kip$

$$q_u := \frac{P_u}{A} = 2.485\ ksf$$

Assume a 16" x 16" column base plate, $b_{bp} := 16\ in$ and a W10 Column $d_c := 10\ in$

Critical Section: $c := \frac{b_{bp} + d_c}{4} = 6.5\ in$

Cantilever Length: $l := \frac{a}{2} - c = 41.5\ in$

Footing Minimum Thickness

One-Way Shear $V_u := q_u \cdot b_w \cdot l = 68.747\ kip$

Assume $\rho_w := 0.003$ $\lambda_s := 1$ $\phi := 0.75$ $V_c = 8 \cdot \lambda_s \cdot \lambda \cdot \left(\rho_w\right)^{\frac{1}{3}} \cdot \sqrt{f'c} \cdot b_w \cdot d > V_u$

Minimum d: $$d_{req} := \frac{V_u}{\phi \cdot 8 \cdot \lambda_s \cdot \lambda \cdot \left(\rho_w\right)^{\frac{1}{3}} \cdot \sqrt{\frac{f'c}{psi}} \cdot psi \cdot b_w} = 13.085\ in$$

From ACI 318-19 Table 20.5.1.3.1, concrete cover needs to be $cover := 3\ in$

Assume #9 rebar, $d_r := 1.128\ in$

Required Total Thickness: $h_{req} := d_{req} + cover + d_r + \frac{d_r}{2} = 17.777\ in$

$$\therefore\ h := 18\ in$$

$$d := h - cover - d_r - \frac{d_r}{2} = 13.308\ in$$

$$V_c := 8 \cdot \lambda_s \cdot \lambda \cdot \left(\rho_w\right)^{\frac{1}{3}} \cdot \sqrt{\frac{f'c}{psi}} \cdot psi \cdot b_w \cdot d = 93.228\ kip$$

$\phi \cdot V_c = 69.921\ kip$ $\phi V_c > V_u$ $V_u = 68.747\ kip$ OK

Concrete Quantity from Foundations:

Spread Footings For Columns (4):

Size: $w_{f1} := 8\ ft$ $l_{f1} := 8\ ft$ $t_{f1} := 18\ in$

Total Volume: $V_F := \left(w_{f1} \cdot l_{f1} \cdot t_{f1}\right) \cdot 4 = 384\ ft^3$

Grade Beams (4):

Size: $h := 18\ in$ $b := 12\ in$ $l := 30\ ft$

Total Volume: $V_{gb} := \left(h \cdot b \cdot l\right) \cdot 4 = 180\ ft^3$

Slab Concrete Volume:

Slab Thickness: $t_s := 4\ in$ Slab on Grade thickness: $t_{sg} := 6\ in$

Floor Area: $A_f := 30\ ft \cdot 30\ ft = 900\ ft^2$

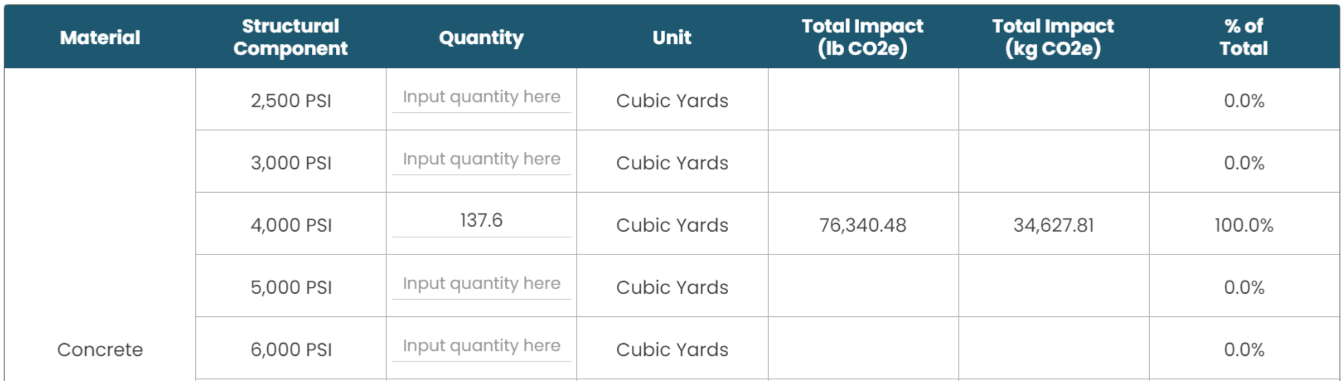
Slab Volume: $V_{slabs} := \left(A_f \cdot t_s\right) + \left(A_f \cdot t_{sg}\right) = 750\ ft^3$

Total Volume of Concrete in Structure:

$V_{total} := V_{walls} + V_{slabs} + V_F + V_{gb} = 3714\ ft^3$ $V_{total} = 137.6\ yd^3$

Carbon Content: $CC_{12} = 76341\ lbco2e$ (ECOM SE2050 Carbon Calculator Output)

ECOM SE 2050 Output:



Material	Structural Component	Quantity	Unit	Total Impact (lb CO2e)	Total Impact (kg CO2e)	% of Total
Concrete	2,500 PSI	Input quantity here	Cubic Yards			0.0%
	3,000 PSI	Input quantity here	Cubic Yards			0.0%
	4,000 PSI	137.6	Cubic Yards	76,340.48	34,627.81	100.0%
	5,000 PSI	Input quantity here	Cubic Yards			0.0%
	6,000 PSI	Input quantity here	Cubic Yards			0.0%

Thermal Mass Design Example

Design Constants:

Structural Layout: 2-story frame, 30'x30' bay, 10' floor height

Concrete Composition: Normal Weight Concrete: Density $\gamma := 150\ pcf$

Compressive Strength: $f'c := 4000\ psi$

Composite Floor Slab: 4" Slab on 3" Metal Deck, 69 PSF

Slab on Grade: 6" Floor Slab on grade

Loading:

Floor Live Load: $L_f := 100\ psf$

Floor Dead Load: $d := 25\ psf$

$d_{sw} := 69\ psf$ Slab Self-Weight (Vulcraft Manual)

$D_f := 94\ psf$

Unfactored Load on Floor: $w_f := D_f + L_f = 194\ psf$

Factored Load on Floor: $w_F := 1.2 \cdot D_f + 1.6 \cdot L_f = 272.8\ psf$

Roof Live Load: $L_r := 20\ psf$

Roof Dead Load: $D_r := 20\ psf$

Unfactored Load on Roof: $w_r := D_r + L_r = 40\ psf$

Factored Load on Roof: $w_R := 1.2 \cdot D_r + 1.6 \cdot L_r = 56\ psf$

This wall will be a built up section, 3" of concrete on the exterior, 2" of rigid insulation, and 9" of concrete on the interior

2" of Rigid Insulation weight is assumed negligible

Design 4 - Insulated Panel Wall Design:

Wall Thickness: $t_{ICP} := 9\ in + 3\ in = 12\ in$

Wall Area: $A_w := 30\ ft \cdot 10\ ft = 300\ ft^2$

Total Concrete Wall Area (two floors): $A := (4 \cdot A_w) \cdot 2 = 2400\ ft^2$

Volume of Walls Concrete: $V_{walls} := A \cdot t_{ICP} = 2400\ ft^3$

Loading on Columns for Foundations:

Height of Walls: $h_w := 10\ ft$

Weight of Walls: $w_w := \gamma \cdot h_w \cdot t_{ICP} = 1500\ plf$

Length of Walls on Column: $l_w := 30\ ft$ 15 feet from each corner

Column Load from wall on second level: $P_w := w_w \cdot l_w = 45\ kip$

Tributary Area: $t_a := 15\ ft \cdot 15\ ft = 225\ ft^2$

Unfactored Load on Columns: $P_{col.unf} := \left(\left(w_f + w_r\right) \cdot t_a\right) + P_w = 97.65\ kip$

Grade Beam Design:

Load on Grade Beam = Self Weight of First Floor Wall and Self Weight of Beam

Wall Thickness: $t_{ICP} := 12\ in$

Wall Height: $h_w := 10\ ft$

Length of Wall: $l_w := 30\ ft$

Self Weight of Wall: $w_w := \gamma \cdot t_{ICP} \cdot h_w = 1.5\ \frac{kip}{ft}$

Beam Dimensions:

Assume Height: $h := 18\ in$

Depth of Steel: $d := 14.5\ in$

Width of Beam: $b := 14\ in$ Increased to meet wall width

Self Weight of Beam: $w_b := \gamma \cdot h \cdot b = 0.263\ \frac{kip}{ft}$

$f_y := 60000\ psi$ $f'c := 4000\ psi$ $\beta := .85$ $l_b := 30\ ft$

Factored Load: $W_u := 1.2 \cdot (w_w + w_b) = 2.115\ \frac{kip}{ft}$

Design Moment: $M := \frac{W_u \cdot {l_w}^2}{8} = 237.938\ kip \cdot ft$

$A_s = \frac{M}{4 \cdot d} = \frac{232.875}{4 \cdot 12} = 4.852\ in^2$ Use (5) #9 Rebar

$A_s := 5.0\ in^2$

$a := \frac{A_s \cdot f_y}{0.85 \cdot f'c \cdot b} = 6.3\ in$

$\phi M_n := 0.9 \cdot A_s \cdot f_y \cdot \left(d - \frac{a}{2}\right) = 255.3\ kip \cdot ft$ $O.K.$

$c := \frac{a}{\beta} = 7.415\ in$

$\varepsilon_T := \frac{d - c}{c} \cdot 0.003 = 0.0029$ $\varepsilon_T \le 0.005$ Good

Reactions From Grade Beam to Spread Footing:

Unfactored Load: $w_{un} := w_b + w_w = 1.763\ \frac{kip}{ft}$

$P_{un} := w_{un} \cdot l_w = 52.875\ kip$

Unfactored Reaction: $R_{un} := \frac{P_{un}}{2} = 26.438\ kip$

Factored Load: $W_u = 2.115\ \frac{kip}{ft}$

$P_{fact} := W_u \cdot l_w = 63.45\ kip$

Factored Reaction: $R_u := \frac{P_{fact}}{2} = 31.725\ kip$

Unfactored Load For Foundations: $P := P_{col.unf} + R_{un} = 124.088\ kip$

Foundation Design:

Spread Footing under Columns

1. Size of Footing

Soil Bearing Capacity: $p := 2000\ psf$ (Assumed Value)

Required Minimum Size: $A_{req} := \frac{P}{p} = 62.044\ ft^2$

Assume square, side dimension: $a := \sqrt{A_{req}} = 7.877\ ft$

Will use 8' x 8'

$a := 8\ ft$ $A := a^2 = 64\ ft^2$

2. Thickness of Footing

$f'c := 4000\ psi$ normal weight concrete $\lambda := 1$

One-way shear: $b_w := a = 96\ in$

Factored Load on Columns: $P_u := \left(\left(w_F + w_R\right) \cdot t_a\right) + \left(1.2 \cdot P_w\right) + R_u = 159.705\ kip$

$$q_u := \frac{P_u}{A} = 2.495\ \boldsymbol{ksf}$$

Assume a 16" x 16" column base plate, $b_{bp} := 16\ \boldsymbol{in}$ and a W10 Column $d_c := 10\ \boldsymbol{in}$

Critical Section: $c := \frac{b_{bp} + d_c}{4} = 6.5\ \boldsymbol{in}$

Cantilever Length: $l := \frac{a}{2} - c = 41.5\ \boldsymbol{in}$

Footing Minimum Thickness

One-Way Shear $V_u := q_u \cdot b_w \cdot l = 69.039\ \boldsymbol{kip}$

Assume $\rho_w := 0.003$ $\lambda_s := 1$ $\phi := 0.75$ $V_c = 8 \cdot \lambda_s \cdot \lambda \cdot \left(\rho_w\right)^{\frac{1}{3}} \cdot \sqrt{f'c} \cdot b_w \cdot d > V_u$

Minimum d: $$d_{req} := \frac{V_u}{\phi \cdot 8 \cdot \lambda_s \cdot \lambda \cdot \left(\rho_w\right)^{\frac{1}{3}} \cdot \sqrt{\frac{f'c}{\boldsymbol{psi}}} \cdot \boldsymbol{psi} \cdot b_w} = 13.14\ \boldsymbol{in}$$

From ACI 318-19 Table 20.5.1.3.1, concrete cover needs to be $cover := 3\ \boldsymbol{in}$

Assume #9 rebar, $d_r := 1.128\ \boldsymbol{in}$

Required Total Thickness: $h_{req} := d_{req} + cover + d_r + \frac{d_r}{2} = 17.832\ \boldsymbol{in}$

$$\therefore\ h := 18\ \boldsymbol{in}$$

$$d := h - cover - d_r - \frac{d_r}{2} = 13.308\ \boldsymbol{in}$$

$$V_c := 8 \cdot \lambda_s \cdot \lambda \cdot \left(\rho_w\right)^{\frac{1}{3}} \cdot \sqrt{\frac{f'c}{\boldsymbol{psi}}} \cdot \boldsymbol{psi} \cdot b_w \cdot d = 93.228\ \boldsymbol{kip}$$

$\phi \cdot V_c = 69.921\ \boldsymbol{kip}$ $\phi V_c > V_u$ $V_u = 69.039\ \boldsymbol{kip}$ OK

Concrete Quantity from Foundations:

Spread Footings For Columns (4):

Size: $w_{f1} := 8\ ft$ $l_{f1} := 8\ ft$ $t_{f1} := 18\ in$

Total Volume: $V_F := \left(w_{f1} \cdot l_{f1} \cdot t_{f1}\right) \cdot 4 = 384\ ft^3$

Grade Beams (4):

Size: $h := 18\ in$ $b := 14\ in$ $l := 30\ ft$

Total Volume: $V_{gb} := \left(h \cdot b \cdot l\right) \cdot 4 = 210\ ft^3$

Slab Concrete Volume:

Slab Thickness: $t_s := 4\ in$ Slab on Grade thickness: $t_{sg} := 6\ in$

Floor Area: $A_f := 30\ ft \cdot 30\ ft = 900\ ft^2$

Slab Volume: $V_{slabs} := \left(A_f \cdot t_s\right) + \left(A_f \cdot t_{sg}\right) = 750\ ft^3$

Total Volume of Concrete in Structure:

$$V_{total} := V_{walls} + V_{slabs} + V_F + V_{gb} = 3744\ ft^3 \qquad V_{total} = 138.7\ yd^3$$

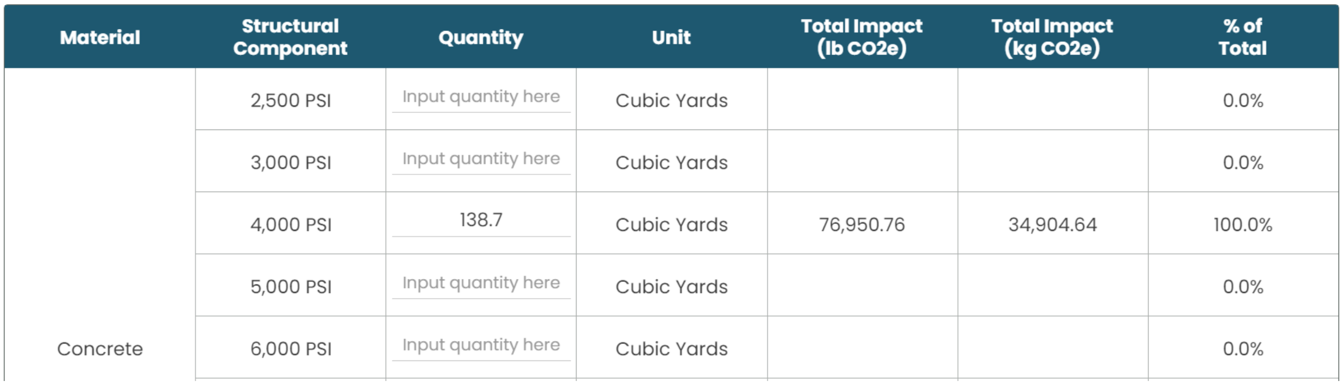
Rigid Insulation Carbon Content:

Square Footage: $A_{ins} := 2400\ ft^2$ Insulation Carbon Value per sf: $5.5\ psf$

Insulation Carbon Content: $CC_{ins} := A_{ins} \cdot 5.5\ psf = 13200\ lbf$

Carbon Content: $CC_{ICP} = 76951 + 13200 = 90151\ lbco2e$ (ECOM SE2050 Carbon Calculator Output)

ECOM SE 2050 Output:



Material	Structural Component	Quantity	Unit	Total Impact (lb CO2e)	Total Impact (kg CO2e)	% of Total
Concrete	2,500 PSI	Input quantity here	Cubic Yards			0.0%
	3,000 PSI	Input quantity here	Cubic Yards			0.0%
	4,000 PSI	138.7	Cubic Yards	76,950.76	34,904.64	100.0%
	5,000 PSI	Input quantity here	Cubic Yards			0.0%
	6,000 PSI	Input quantity here	Cubic Yards			0.0%

RS-Means Construction and Production Costs

Constant Costs for Concrete Elements

Costs for these members do not change between designs because the member sizes did not change drastically enough according to RS-Means

Spread Footings: Cost per Footing, based on 7'-6" square 18" deep footing

Material: $\$790$

Installation: $\$725$ 4 Footings:

Total: $\$1515$ $4 \cdot 1515 = \$6060$

Grade Beams: Cost per L.F., based on 15 foot span T-Beam

Material: $\$296$

Installation: $\$24.50$ 120 Linear Feet of grade beam

Total: $\$320.50$ $120 \cdot 320.50 = \$38418$

Floor Construction: Cost per S.F., based on 30'x30' bay size with 125 superimposed load

Material: $\$30$

Installation: $\$12.30$ Floor Area: $A_f := 900\ ft^2$

Total: $\$42.30$ $42.30 \cdot A_f = \$38070$

Slab on Grade: Cost per S.F., based on 6" slab non-industrial

Material: $\$4.26$

Installation: $\$3.46$ Floor Area: $A_f := 900\ ft^2$

Total: $\$7.72$ $7.72 \cdot A_f = \$6948$

6-Inch Wall Cost:

Exterior Walls: Cost per S.F., 6" thick wall with plain finish

Material: $\$8.90$

Installation: $\$19.90$

Total: $\$28.80$

Total Wall Area (2 Floors):

$$A_w := 4 \cdot (30\ ft \cdot 20\ ft) = 2400\ ft^2$$

$$28.80 \cdot A_w = \$69120$$

Manhattan, KS Location Factor: $F_{KS} := 0.9$

Minneapolis, MN Location Factor: $F_{MN} := 1.07$

Phoenix, AZ Location Factor: $F_{AZ} := 0.91$

Total Concrete Cost:

Manhattan, KS $C_{6.ks} := F_{KS} \cdot (6060 + 38418 + 31005 + 5607 + 69120) = 135189$

$$C_{6.ks} = \$135189$$

Minneapolis, MN $C_{6.mn} := F_{MN} \cdot (6060 + 38418 + 31005 + 5607 + 69120) = 160724.7$

$$C_{6.mn} = \$160725$$

Phoenix, AZ $C_{6.az} := F_{AZ} \cdot (6060 + 38418 + 31005 + 5607 + 69120) = 136691.1$

$$C_{6.az} = \$136692$$

8-Inch Wall Cost:

Exterior Walls: Cost per S.F., 8" thick wall with plain finish

Material: $\$10.20$

Installation: $\$20.50$ Total Wall Area: $A_w := 4 \cdot (30\ ft \cdot 20\ ft) = 2400\ ft^2$

Total: $\$30.70$ $30.70 \cdot A_w = \$73680$

Manhattan, KS Location Factor: $F_{KS} := 0.9$

Minneapolis, MN Location Factor: $F_{MN} := 1.07$

Phoenix, AZ Location Factor: $F_{AZ} := 0.91$

Total Concrete Cost:

Manhattan, KS $C_{8.ks} := F_{KS} \cdot (6060 + 38418 + 31005 + 5607 + 73680) = 139293$

$C_{8.ks} = \$139293$

Minneapolis, MN $C_{8.mn} := F_{MN} \cdot (6060 + 38418 + 31005 + 5607 + 73680) = 165603.9$

$C_{8.mn} = \$165304$

Phoenix, AZ $C_{8.az} := F_{AZ} \cdot (6060 + 38418 + 31005 + 5607 + 73680) = 140840.7$

$C_{8.az} = \$140841$

12-Inch Wall Cost:

Exterior Walls: Cost per S.F., 12" thick wall with plain finish

Material: $\$12.85$

Installation: $\$21.50$ Total Wall Area: $A_w := 4 \cdot (30\ ft \cdot 20\ ft) = 2400\ ft^2$

Total: $\$34.35$ $34.35 \cdot A_w = \$82440$

Manhattan, KS Location Factor: $F_{KS} := 0.9$

Minneapolis, MN Location Factor: $F_{MN} := 1.07$

Phoenix, AZ Location Factor: $F_{AZ} := 0.91$

Total Concrete Cost:

Manhattan, KS $C_{12.ks} := F_{KS} \cdot (6060 + 38418 + 31005 + 5607 + 82440) = 147177$

$C_{12.ks} = \$147177$

Minneapolis, MN $C_{12.mn} := F_{MN} \cdot (6060 + 38418 + 31005 + 5607 + 82440) = 174977.1$

$C_{12.mn} = \$174978$

Phoenix, AZ $C_{12.az} := F_{AZ} \cdot (6060 + 38418 + 31005 + 5607 + 82440) = 148812.3$

$C_{12.az} = \$148813$

Insulated Panel Wall Cost:

Exterior Walls: Cost per S.F., Insulated Concrete Panel with plain finish

Material: $\$17.55$

Installation: $\$32.45$ Total Wall Area: $A_w := 4 \cdot (30\ ft \cdot 20\ ft) = 2400\ ft^2$

Total: $\$50.00$ $50.00 \cdot A_w = \$120000$

Manhattan, KS Location Factor: $F_{KS} := 0.9$

Minneapolis, MN Location Factor: $F_{MN} := 1.07$

Phoenix, AZ Location Factor: $F_{AZ} := 0.91$

Total Concrete Cost:

Manhattan, KS $C_{IP.ks} := F_{KS} \cdot (6060 + 38418 + 31005 + 5607 + 120000) = 180981$

$C_{IP.ks} = \$180981$

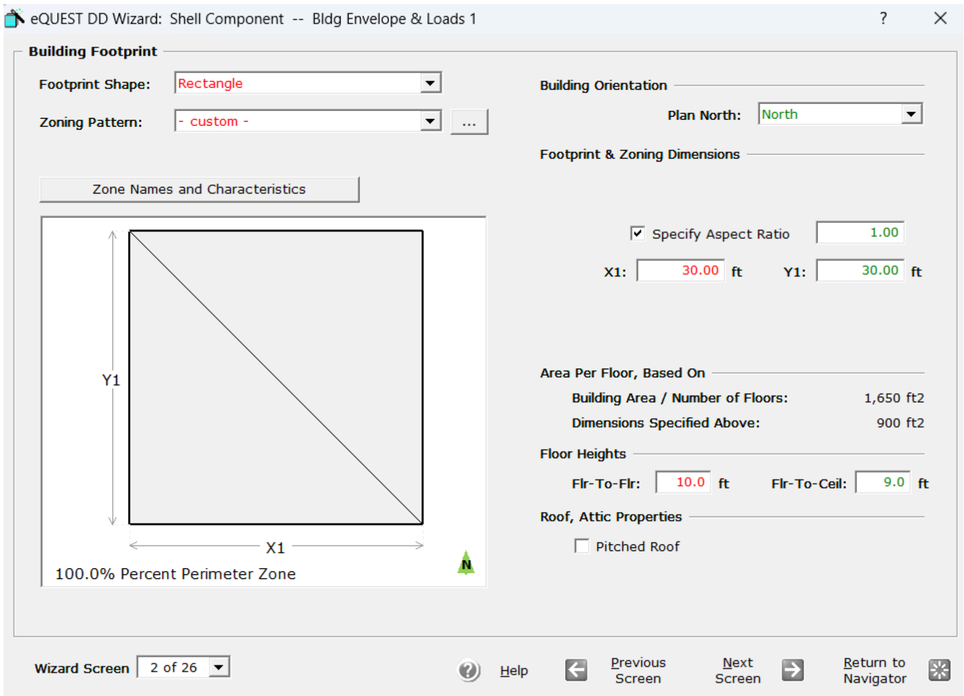
Minneapolis, MN $C_{IP.mn} := F_{MN} \cdot (6060 + 38418 + 31005 + 5607 + 120000) = 215166.3$

$C_{IP.mn} = \$215167$

Phoenix, AZ $C_{IP.az} := F_{AZ} \cdot (6060 + 38418 + 31005 + 5607 + 120000) = 182991.9$

$C_{IP.az} = \$182992$

Appendix B - eQuest Input Data


eQUEST DD Wizard: Shell Component -- Bldg Envelope & Loads 1

Building Footprint

Footprint Shape: Rectangle
Zoning Pattern: - custom -

Building Orientation
Plan North: North

Footprint & Zoning Dimensions
☑ Specify Aspect Ratio 1.00
X1: 30.00 ft Y1: 30.00 ft

Area Per Floor, Based On
Building Area / Number of Floors: 1,650 ft2
Dimensions Specified Above: 900 ft2

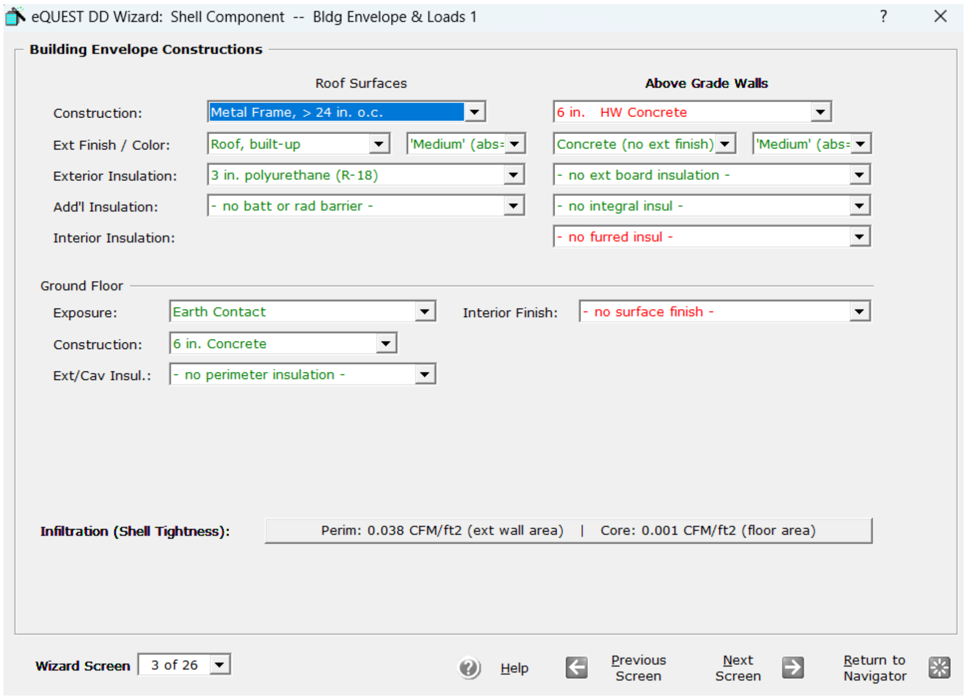
Floor Heights
Flr-To-Flr: 10.0 ft Flr-To-Ceil: 9.0 ft

Roof, Attic Properties
☐ Pitched Roof

100.0% Percent Perimeter Zone

Wizard Screen 2 of 26

Figure 13: eQuest Building Footprint


eQUEST DD Wizard: Shell Component -- Bldg Envelope & Loads 1

Building Envelope Constructions

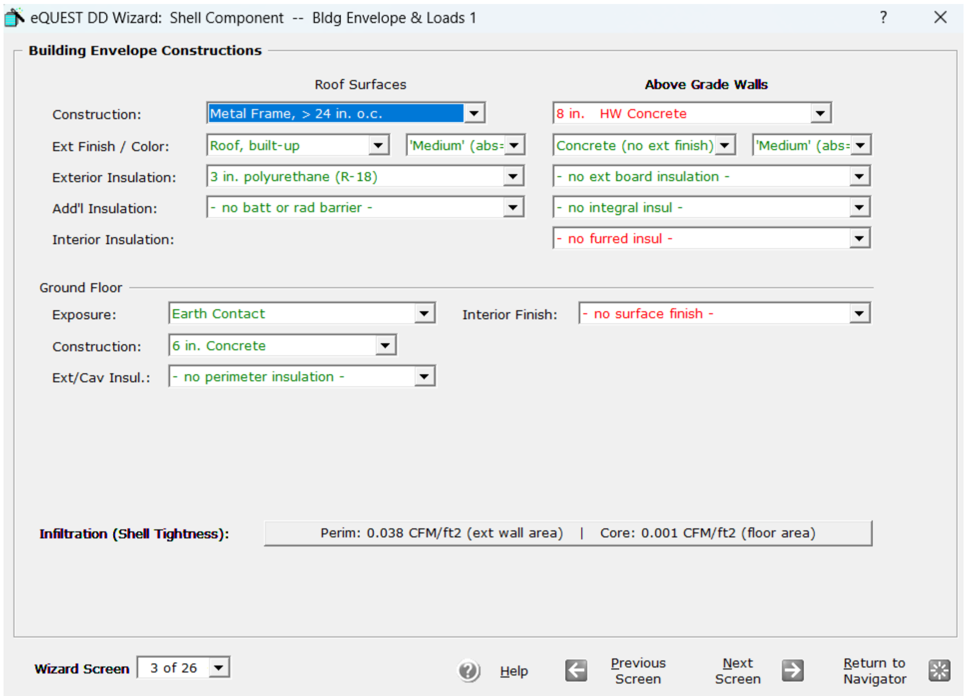
	Roof Surfaces		Above Grade Walls	
Construction:	Metal Frame, > 24 in. o.c.		6 in. HW Concrete	
Ext Finish / Color:	Roof, built-up	'Medium' (abs=	Concrete (no ext finish)	'Medium' (abs=
Exterior Insulation:	3 in. polyurethane (R-18)		- no ext board insulation -	
Add'l Insulation:	- no batt or rad barrier -		- no integral insul -	
Interior Insulation:			- no furred insul -	

Ground Floor
Exposure: Earth Contact
Interior Finish: - no surface finish -
Construction: 6 in. Concrete
Ext/Cav Insul.: - no perimeter insulation -

Infiltration (Shell Tightness): Perim: 0.038 CFM/ft2 (ext wall area) | Core: 0.001 CFM/ft2 (floor area)

Wizard Screen 3 of 26

Figure 14: eQuest Building Envelope Constructions for 6” Wall



Building Envelope Constructions

	Roof Surfaces		Above Grade Walls	
Construction:	Metal Frame, > 24 in. o.c.		8 in. HW Concrete	
Ext Finish / Color:	Roof, built-up	'Medium' (abs=	Concrete (no ext finish)	'Medium' (abs=
Exterior Insulation:	3 in. polyurethane (R-18)		- no ext board insulation -	
Add'l Insulation:	- no batt or rad barrier -		- no integral insul -	
Interior Insulation:			- no furred insul -	

Ground Floor

Exposure: Earth Contact

Interior Finish: - no surface finish -

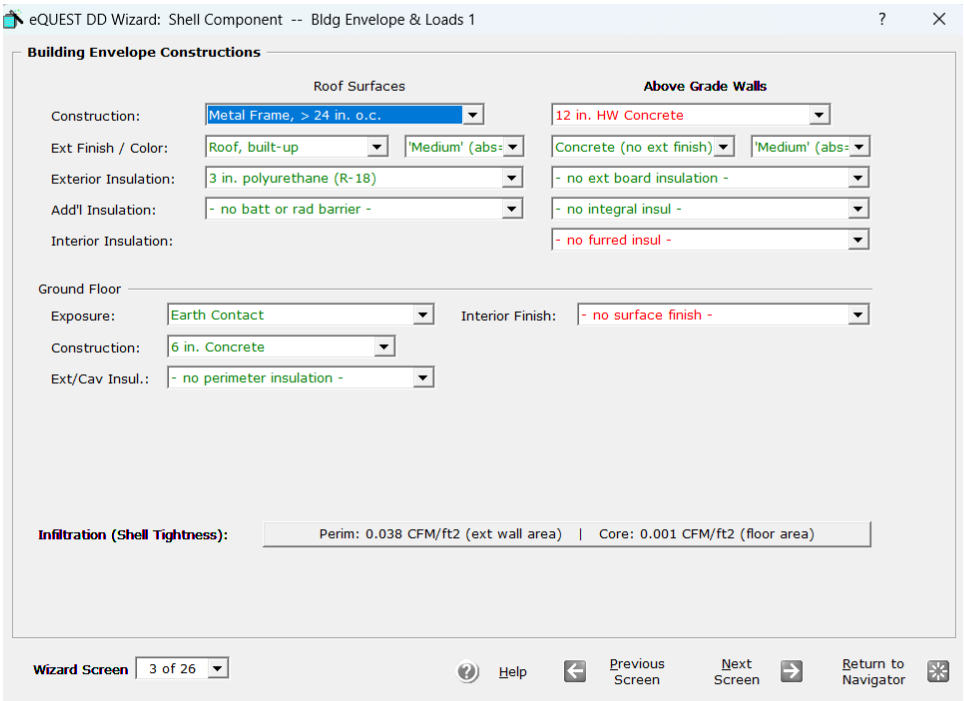
Construction: 6 in. Concrete

Ext/Cav Insul.: - no perimeter insulation -

Infiltration (Shell Tightness): Perim: 0.038 CFM/ft2 (ext wall area) | Core: 0.001 CFM/ft2 (floor area)

Wizard Screen 3 of 26

Figure 15: eQuest Building Envelope Constructions for 8” Wall



Building Envelope Constructions

	Roof Surfaces		Above Grade Walls	
Construction:	Metal Frame, > 24 in. o.c.		12 in. HW Concrete	
Ext Finish / Color:	Roof, built-up	'Medium' (abs=	Concrete (no ext finish)	'Medium' (abs=
Exterior Insulation:	3 in. polyurethane (R-18)		- no ext board insulation -	
Add'l Insulation:	- no batt or rad barrier -		- no integral insul -	
Interior Insulation:			- no furred insul -	

Ground Floor

Exposure: Earth Contact

Interior Finish: - no surface finish -

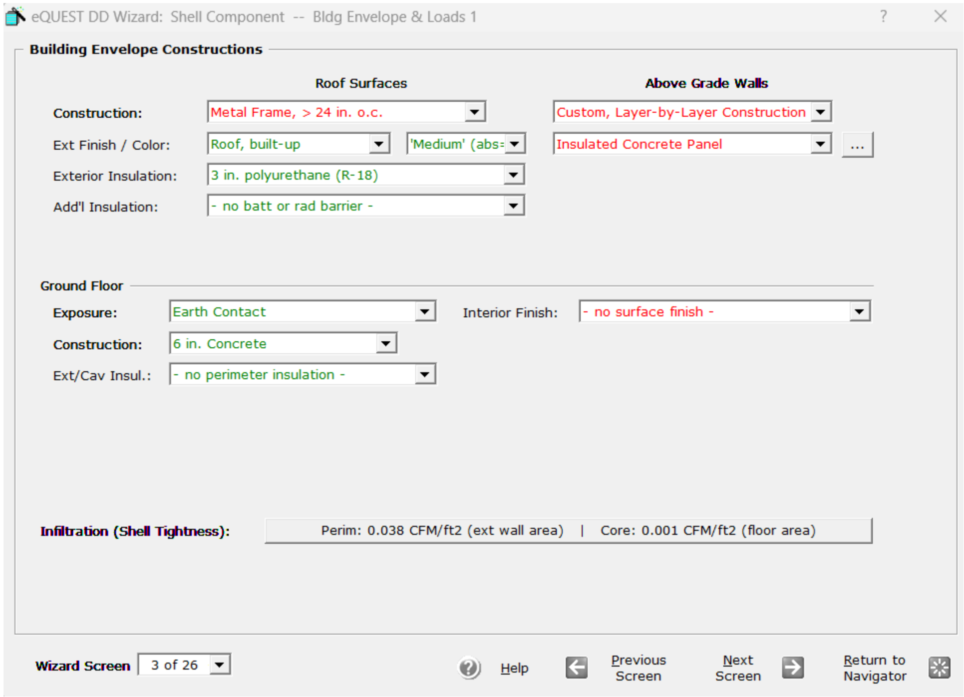
Construction: 6 in. Concrete

Ext/Cav Insul.: - no perimeter insulation -

Infiltration (Shell Tightness): Perim: 0.038 CFM/ft2 (ext wall area) | Core: 0.001 CFM/ft2 (floor area)

Wizard Screen 3 of 26

Figure 16: eQuest Building Envelope Constructions for 12” Wall



Building Envelope Constructions

	Roof Surfaces		Above Grade Walls
Construction:	Metal Frame, > 24 in. o.c.		Custom, Layer-by-Layer Construction
Ext Finish / Color:	Roof, built-up	'Medium' (abs=	Insulated Concrete Panel
Exterior Insulation:	3 in. polyurethane (R-18)		
Add'l Insulation:	- no batt or rad barrier -		

Ground Floor

Exposure: Earth Contact

Interior Finish: - no surface finish -

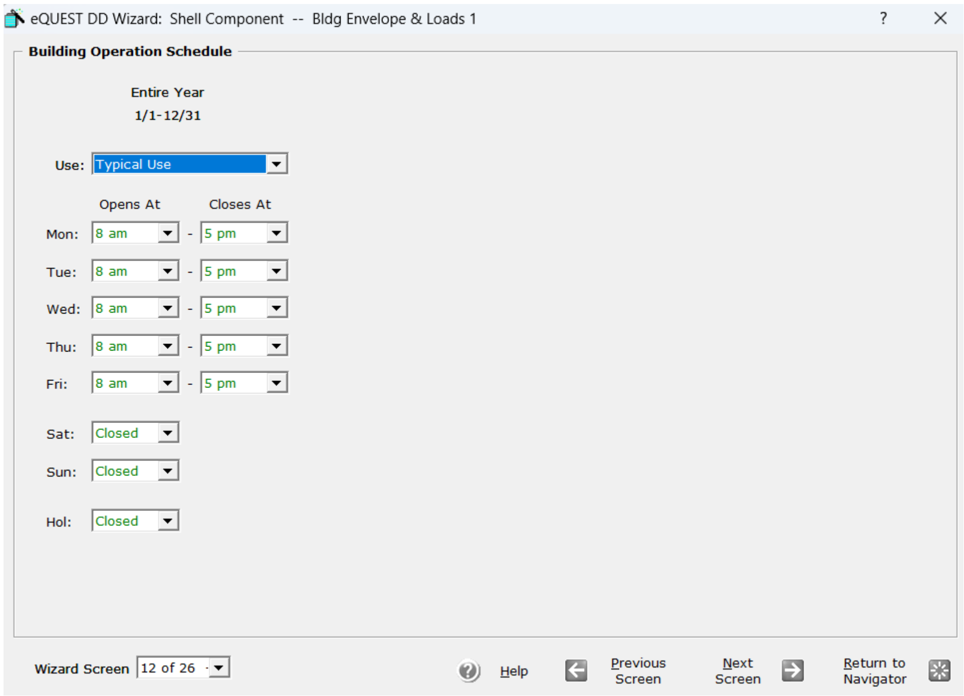
Construction: 6 in. Concrete

Ext/Cav Insul.: - no perimeter insulation -

Infiltration (Shell Tightness): Perim: 0.038 CFM/ft2 (ext wall area) | Core: 0.001 CFM/ft2 (floor area)

Wizard Screen: 3 of 26

Figure 17: eQuest Building Envelope Constructions for ICP



Building Operation Schedule

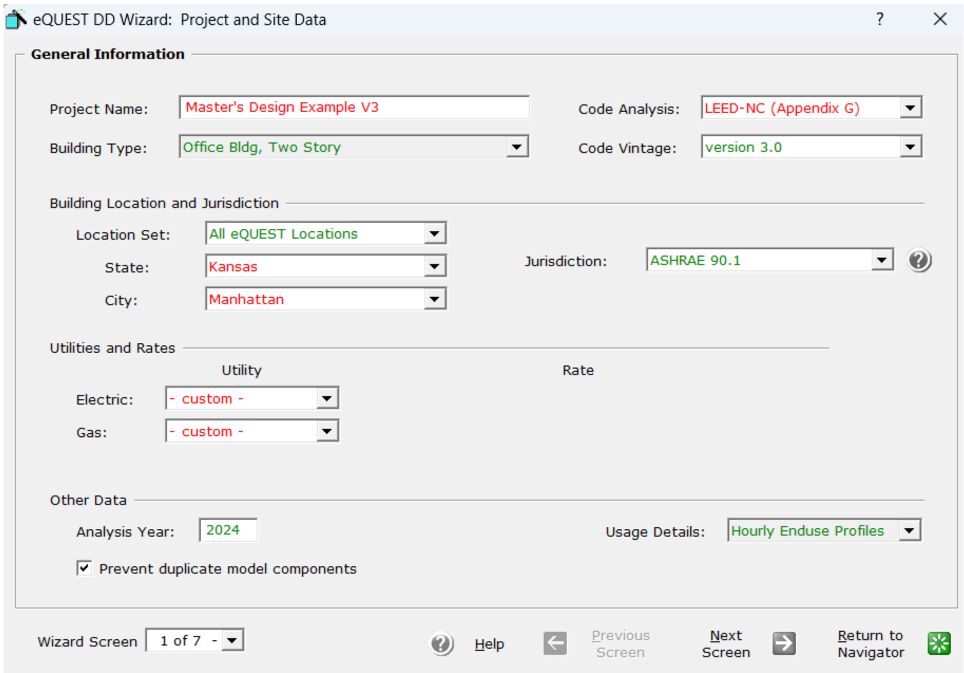
Entire Year
1/1-12/31

Use: Typical Use

	Opens At	Closes At
Mon:	8 am	5 pm
Tue:	8 am	5 pm
Wed:	8 am	5 pm
Thu:	8 am	5 pm
Fri:	8 am	5 pm
Sat:	Closed	
Sun:	Closed	
Hol:	Closed	

Wizard Screen: 12 of 26

Figure 18: eQuest Building Operation Schedule



General Information

Project Name: Master's Design Example V3

Building Type: Office Bldg, Two Story

Code Analysis: LEED-NC (Appendix G)

Code Vintage: version 3.0

Building Location and Jurisdiction

Location Set: All eQUEST Locations

State: Kansas

City: Manhattan

Jurisdiction: ASHRAE 90.1

Utilities and Rates

	Utility	Rate
Electric:	- custom -	
Gas:	- custom -	

Other Data

Analysis Year: 2024

Usage Details: Hourly Enduse Profiles

☑ Prevent duplicate model components

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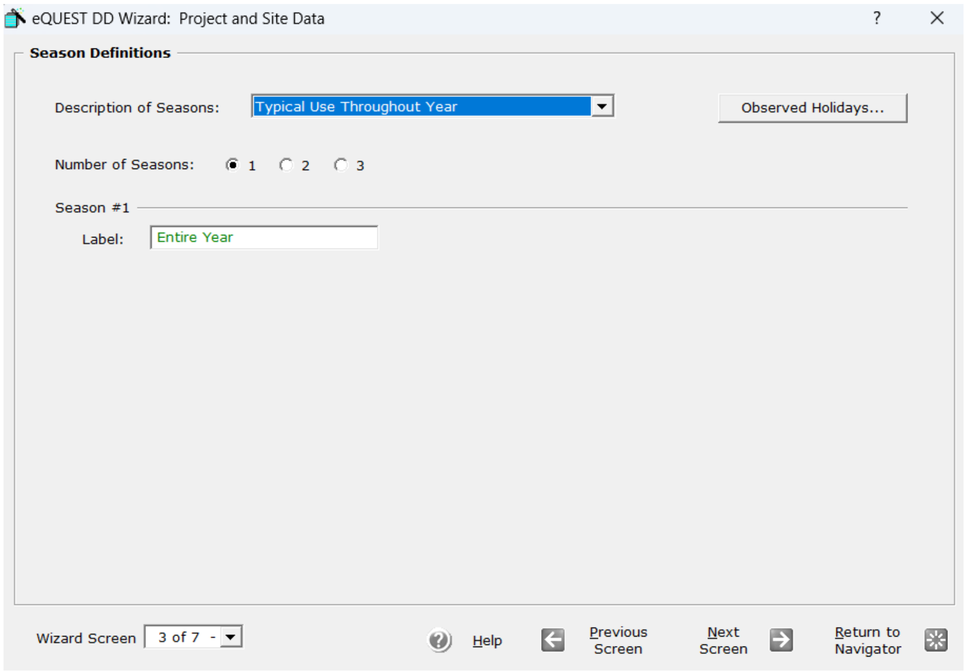
Figure 19: eQuest General Information Page (Manhattan, KS Example)



Season Definitions

Description of Seasons: Typical Use Throughout Year

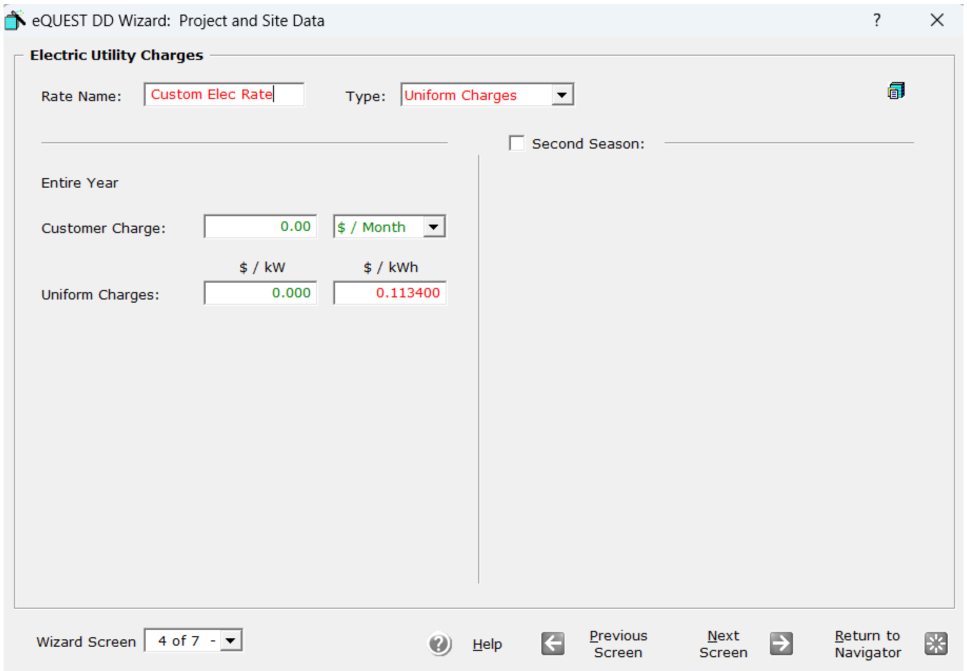
Number of Seasons: ● 1 ○ 2 ○ 3

Season #1

Label: Entire Year

Wizard Screen 3 of 7 -

Figure 20: eQuest Season Definitions



Electric Utility Charges

Rate Name: Custom Elec Rate

Type: Uniform Charges

☐ Second Season:

Entire Year

Customer Charge: 0.00 $ / Month

	$ / kW	$ / kWh
Uniform Charges:	0.000	0.113400

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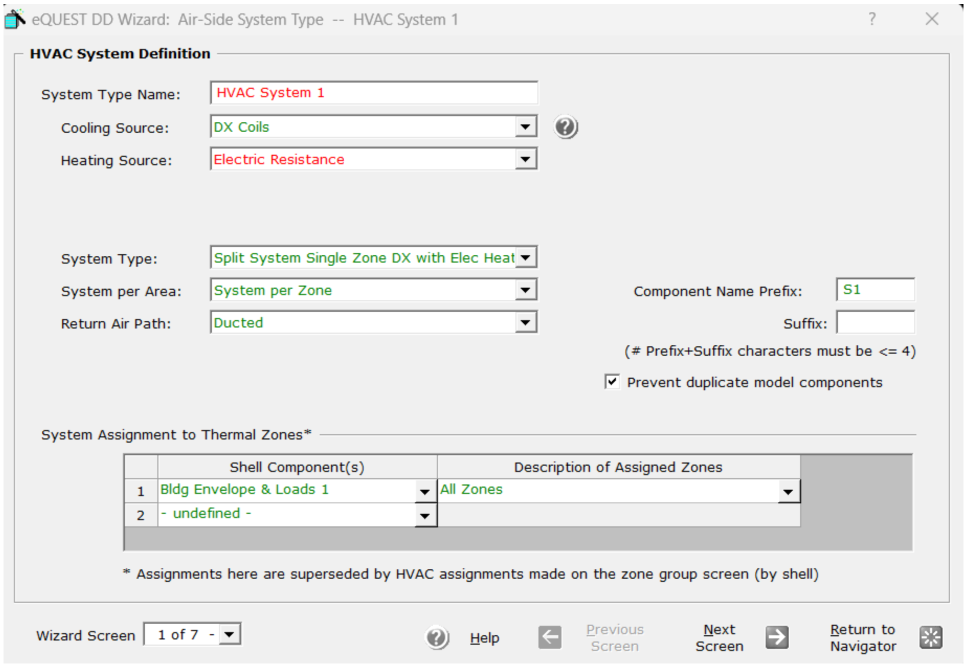
Figure 21: eQuest Electric Utility Rates Page (Manhattan, KS Example)



HVAC System Definition

System Type Name: HVAC System 1

Cooling Source: DX Coils

Heating Source: Electric Resistance

System Type: Split System Single Zone DX with Elec Heat

System per Area: System per Zone

Return Air Path: Ducted

Component Name Prefix: S1

Suffix:

(# Prefix+Suffix characters must be <= 4)

☑ Prevent duplicate model components

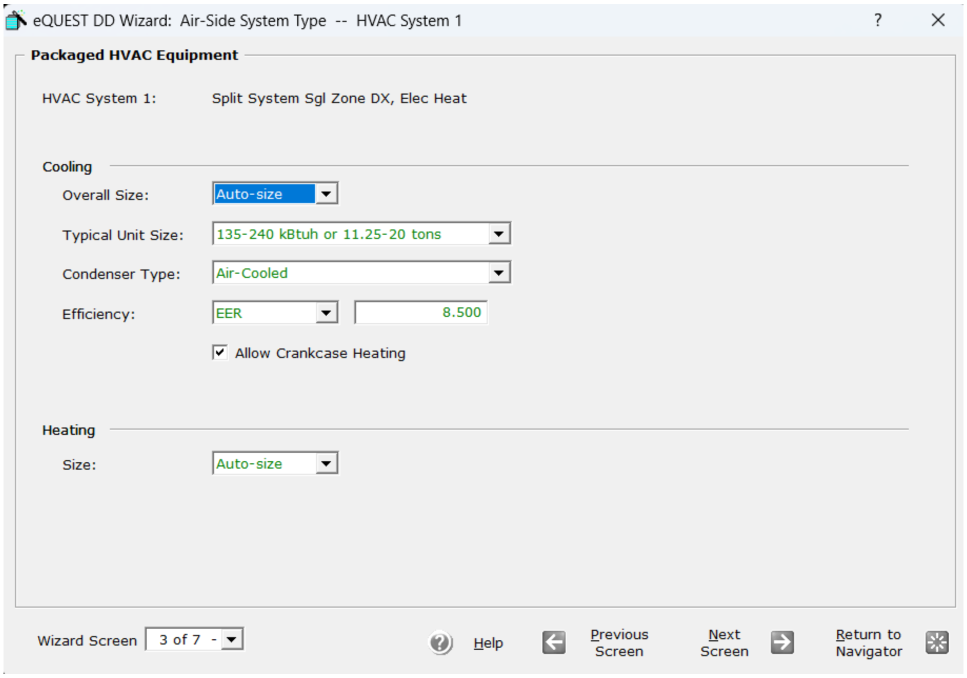
System Assignment to Thermal Zones*

	Shell Component(s)	Description of Assigned Zones
1	Bldg Envelope & Loads 1	All Zones
2	- undefined -	

* Assignments here are superseded by HVAC assignments made on the zone group screen (by shell)

Wizard Screen 1 of 7

Figure 22: eQuest HVAC System description



Packaged HVAC Equipment

HVAC System 1: Split System Sgl Zone DX, Elec Heat

Cooling

Overall Size: Auto-size

Typical Unit Size: 135-240 kBtuh or 11.25-20 tons

Condenser Type: Air-Cooled

Efficiency: EER 8.500

☑ Allow Crankcase Heating

Heating

Size: Auto-size

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Figure 23: eQuest HVAC System Size