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Investigating The Impact Of Thermal Mass Towards Energy Efficient Housing In Canada

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INVESTIGATING THE IMPACT OF THERMAL MASS TOWARDS ENERGY EFFICIENT HOUSING IN CANADA

By

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ABSTRACT:

The building industry is striving for environmental friendly and energy efficient facility developments, as we have used most of our natural resources for comfortable living. Therefore energy efficient houses are very significant to reduce energy consumption. Thermal mass can be used as one of the many techniques of energy efficiency in the housing industry. Thermal mass can store heat in it which can be released at a later time. This behaviour of thermal mass can play a significant role in heating and cooling energy consumption of houses. This study investigates the impact of thermal mass on heating and cooling energy performance of a detached house and a row attached house, which are two main types of housing in Canada. Energy Plus simulation software has been used in the study. Also the study includes two different climatic conditions in Canada, such as Toronto and Vancouver, to envision how thermal mass behaviour changes with climates. All these different studies show thermal mass has significant impact on reduced energy consumption (15% savings in Vancouver for CCHT house) and lowering indoor air temperature. Other strategies such as insulation high R value, increased south face glazing and reduced glazing U value have been integrated with thermal mass to see energy performance in both climates. It shows more energy reduction than only thermal mass strategy. For instance, in CCHT house insulation high R value with concrete high mass reduces maximum 27% of total energy for Vancouver location.

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1. INTRODUCTION

Buildings contribute to significant energy consumption from early stage of material production to the end of life. The increase in the energy price and growth in the sustainability concern, is leading to a rethink on reduced energy consumption in buildings. One aspect of this achievement of sustainability in the building industry is an increased emphasis on the effect of thermal mass. Construction materials, particularly high density materials such as concrete, brick, stone etc. have the ability to absorb, store and release significant amounts of heat, and this often affects the net energy balance and consumption of the building. Structures built with masonry walls and concrete for decades have shown these advantages because of their inherent thermal mass construction. The absorption and retention ability of thermal mass building components can reduce energy consumption for a period of time by transferring heat in a natural cycle. Thermal mass slows down response times, thus better balancing heating and cooling as well as reducing temperature fluctuations. Generally, with all other factors being constant, a high mass building uses less energy than a similar one with low thermal mass because of the increased heat storage potential of massive components. These factors can also shift the energy demand to off- peak time periods by damping effect (Figure1), potentially reducing the energy cost.

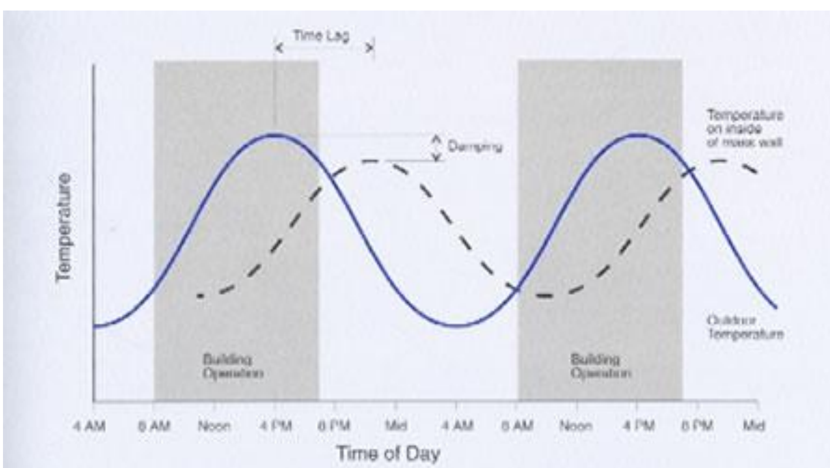

Figure 1 Damping and Energy Demand Shifting of Thermal Mass
(source://www.concretethinker.com/solutions/Thermal-Mass.aspx)

This research investigates the heating and cooling energy demand of residential housing in Toronto and Vancouver location, incorporating different amounts of thermal mass (for instance light, medium and heavy). Also the research aims to investigate the best possible ways (such as insulation high R value, south face glazing, glazing reduced U value etc.) for reduced energy demand with thermal mass.

1.1 ENERGY EFFICIENT HOUSING IN CANADA

A 2009 report on energy efficiency trends in Canada shows that houses use 17 percent of all energy used which is equivalent to 1,422.3 PJ (NRCan, 2011*)*.

In Canadian housing a variety of energy sources are used, including natural gas, electricity, wood; heating oil and propane as primary source of energy. Nevertheless the vast majority of energy used is in the form of natural gas and electricity because of the availability and low cost of these energies relative to oil. Natural gas and electricity also show relative high efficiency ratings as furnace fuel.

The number of households in Canada is increasing because of population growth. The number of household has been increased by 36 percent partly due to 22 percent increase in population since 1990. The number of household with increased living space and more appliances contribute to 11 percent more residential energy usage (1282.1 PJ to 1,422.3 PJ) (NRCan, 2011).

Several factors have affected residential energy use in Canada over the last 20 years. Despite these increase in the overall residential energy use, the intensity of energy usage per square meter has decreased since 1990 because of the energy efficient measures. Energy efficient measures such as R 2000 standard, Energuide, Energy Star etc. have helped a lot to decrease energy consumption per household despite their larger living space and greater use of appliances. The energy intensity has decreased from 129.6 GJ per household in 1990 to 106 GJ per household in 2009 (NRCan, 2011). The intensity of space heating has been decreased from 0.66 GJ/m^2 to 0.50 GJ/m^2 from 1990 to 2009 (though the heating degree days were higher in 2009) (NRCan, 2011). However, Canadians desire for larger houses has increased the overall space heating energy use from previous decades. This caused a 13 percent growth in residential space heating energy in 2009 from 1990 due to the increase in population and number of household (792.3 PJ in 1990 to 893.2 PJ in 2009) (NRCan, 2011).

The following are a list of energy efficiency standards for the new and existing homes that have been in recent use in Canada.

R-2000 Home: R 2000 is a residential house construction program which has been developed by Natural Resources Canada's (NRCan) office of Energy Efficiency with a partnership to residential construction industry. The main goal of this program is to benchmark Canadian houses in the areas of comfort, energy efficiency and environmental impact. It is a voluntary participation certificate program for which houses must meet specifications and performance standards along with R 2000 trained home builders. 2012 R 2000 standard homes are 50% more energy efficient than previously built houses in 2005 mentioned by (Brière, 2012). As of 2009 approximately 10,000 homes have been built as R-2000 standard since the program began in the 1980s . (NRCan, 2011)

Energuide: The Energuide program intends the new homes must be constructed using techniques that will result in 30% less energy usage than those houses built according to building codes (NRCan, 2010). Energuide scales homes on a 0-100 points and for its qualification houses must meet score above 80.

Energy Star:

The ENERGY STAR program for New Homes promotes energy efficiency guidelines that enable new homes to be more energy efficient than those built to minimum provincial building codes, which require Energy Star heating and cooling system, windows, patio doors, skylights and increased insulation for walls and ceilings. The increased efficiency of these homes translates into reduced energy costs for homeowners. Over 20,000 houses have been labelled through the "ENERGY STAR for New Homes" initiative. (NRCan, n.d)

Eco Energy:

The Eco Energy retrofit program provides grants up to $5,000 to help homeowners make their homes more energy-efficient and reduce high energy costs. One of the eligibility criteria include participants to obtain a pre-retrofit evaluation by a certified energy advisor, which uses the Ener Guide Rating System before starting work and a post-retrofit evaluation within program deadlines. The program continued from April 2007 to March 2012. (ecoEnergy, n.d)

"The number of high efficiency new homes labelled in Canada increased fourfold from 2002 to 2006. These homes use 25-30% less energy on average than typical new homes – and are more comfortable for their occupants."(NRCan, n.d)

1.2 THERMAL MASS AND ENERGY EFFICIENT HOUSING

Thermal mass in a building consists of materials used in the building that have the capacity to absorb significant amounts of thermal energy from the sun or other incidental heat sources. This allows excess heat to be absorbed in the summer reducing cooling loads while in the winter it can reduce peak heating loads. Thus materials with high specific heat capacity (which means the heat capacity per unit mass for a material measured in J/kg.K) and density (such as brick, concrete, stone etc.) can be utilized to reduce space heating and cooling in suitable climates. These natural strategies based on thermal mass have most significant scope in climates with large diurnal temperature differences as this allows the excess heat to be removed during the cooler nighttime . Moreover, placement of thermal mass is significant to get the most benefit from it in terms of energy savings and implementation cost. Such as, thermal mass in floors is better and cheaper than using it in walls to get most benefit from this strategy as floors at south face get most sunlight from winter sun.

High thermal mass walls (double brick/masonry, brick veneer/cement particle boards cladding etc.) should be built with proper combination of insulation and thermal mass for the most energy efficiency and indoor comfort. This requires exact zone climate and engineering data for accurate design. Such as, insulation at the exterior side of mass wall performs better than the insulation in interior side. Because, insulation helps thermal mass to retain heat in the interior side of the wall and keeps indoor warm and comfortable in winter. As well as overhangs, amount of glazing surface of the walls (particularly south facing) play important role in cooling/heating strategies.

Passive solar is one of the most efficient design strategies to harness energy from the sun for building heating and cooling. Thermal mass is a significant part in this system which helps storing solar heat in it. Other important elements of passive solar systems are window apertures, shading systems, insulation levels and surface colors. All these combination can reduce building energy consumption to a significant extent. The following Figure shows five elements of passive solar system.

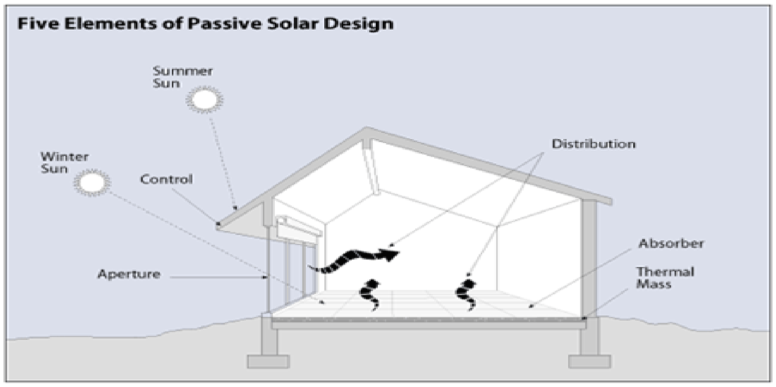

Figure 2 Passive solar design strategies**.(**Source: http://www.house-energy.com/Walls/ThermalMassFloors.html)

1. Aperture (Windows) – Windows face within 30 degrees of true south get most sunlight during winter months when it should not be shaded from 9 a.m. to 3 p.m. Living area's window must be in south while in bedrooms windows must be in north side to prevent over- heating. The amount of windows should be less in north, east and west side of the building to reduce heat loss in colder climates, while allowing adequate sun light.

2. Absorber- The darkened hard surface of the storage element is considered as absorber. The surface of masonry wall, floor and partition stays at direct path of sunlight, which hits and absorb in the dark colored surface as heat.

3. Thermal Mass- Floors and walls with thermal storage materials absorb heat that is very useful for naturally heating homes in colder climates. Such as, concrete is one of the most excellent thermally active materials (1000 J/kg. k specific heat), which can be involved in walls and floors for natural cooling and heating strategies. The only difference between absorber and thermal mass is absorber is the exposed material while thermal mass is an internal material below that surface.

4. Heat Distribution- Passive solar design allows heat to circulate around collection and storage points in different areas of the house. It relies on natural heat transfer through radiation and air convection. Such as if heat gets absorbed in the floor distributes it through the walls and ceilings if the temperature of those surfaces are lower by natural heat transfer strategy. Thus the house keeps heated during winter.

5. Control- Roof overhangs, trees can be used as shade to the window with sufficient natural ventilation during summer months to prevent overheating from the sun.

Thus thermal mass with other factors has the potential to play an important role in reducing energy consumption for space heating and cooling and make the house less energy consumer than other conventional light weight houses.

1.3 THERMAL MASS USE IN ENERGY CONSERVING BUILDINGDESIGN

Thermal mass is a crucial building element in the success of most passive solar heating strategies, active heating strategies and passive cooling strategies. It is usually used to optimize the reliance on mechanical heating and cooling strategies.

1.3.1 PASSIVE HEATING STRATEGIES

Direct Gain- In direct gain system the south facing windows gain heat while windows in the north, west and east side lose more heat than their gain in the winter. It lets the short-wave solar energy enter the building which is then absorbed in the building thermal mass to prevent overheating and stored it for night time use. It should be directly exposed to the sun without any obstruction. The ratio of mass and south face glazing is critical, however a rule of thumb is the mass area needs to exceed the glass area by a factor of 3. (Haglund, Rathmann, n.d) The ratio could be increased up to 9:1 considering the mass type, exposure, thickness, occupancy pattern and energy requirements (Haglund, Rathmann, n.d). In the heating season the exposed thermal mass absorbs direct heat from winter sun through south face window which gets stored in it for night use. Thus it maintains comfortable temperature in daytime and reduces heating load by releasing stored heat at night time. During cooling season south face window with exposed mass can overheat the space if the mass is not cooled properly at night; therefore it is important to minimize the direct sun entering this space, to limit overheating. Nevertheless thermal mass in the space may reduce the overheating by absorbing the thermal energy entering the space. The following table shows the rules for estimating thermal mass in direct gain systems. The table specifies minimum requirements of the thermal mass, additional thermal mass might be helpful for reducing extreme indoor temperatures. It is useful to keep the mass as close as possible to the floors for better structural and thermal performance. Medium and dark colour massive elements absorb heat more while light colourd elements reflect heat. So darker colours on the thermally massive elements will improve absorbtion of heat. For widely surfaced mass translucent glazing might be useful that release diffused radiantion to evenly distribute heat in the space (Lechner N, 2001).

Thermal mass	Thickness	Surface area per sq. ft/sq.m of glazing)
Masonry or concrete exposed to direct radiation	4 to 6 in (.10 to .15m)	3 ft^2 ($.27m^2$)
Masonry or concrete exposed to reflected radiation	2 to 4 in (.05 to.10 m)	6 ft^2 ($.55m^2$)
Water	About 6 in (.15 m)	About ½ ft^2 (0.05 m^2)

Table 1 Estimation of thermal mass in direct gain system (source: Lechner N, 2001)

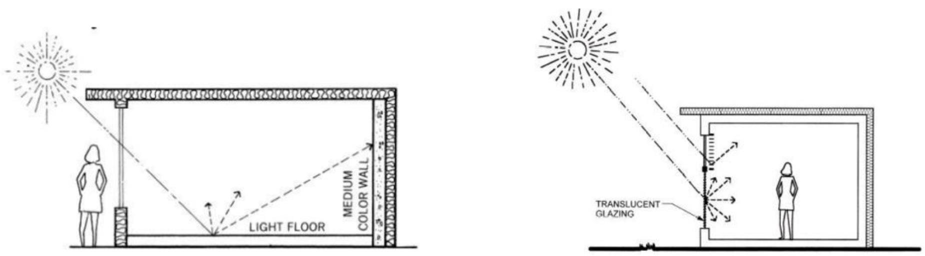

Figure 3 Direct Heat Gains (left: light colour non-massive floor, right: diffuse radiation) in Passive Heating Strategies (source: Lechner N, 2001)

Indirect Gain - When direct heat from sun is not required, indirect gain can help maintain thermal comfort. In indirect gain thermal mass separates the collector from conditioned space which manages heat flow through separator thermal mass's (Figure 4) time lag property. Operable vents and other convective connections between space and collector allow warm air to enter in the daytime which makes indirect gains to the thermal mass. When direct gain system heats early in the day from delighted sunshine, indirect gains can absorb and store heat for night time use. Thus the right combination of two systems can make better thermal and visual comfort in houses. Indirect strategies are trombe walls, water walls, roof ponds etc.

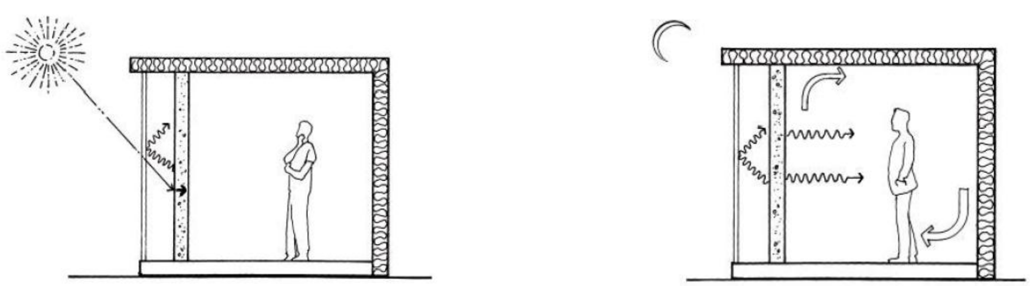

Figure 4 Indirect Heat Gains in Passive Heating Strategies (source: Lechner N, 2001)

1.3.2 PASSIVE COOLING STRATEGIES

High Mass Cooling - In High mass passive cooling strategies mass stores internal heat gains and it is flushed out at night by natural ventilation or fans. Although mechanical forced air handling system make a good combination for flushing heat from walls and floors.

Court yard Cooling - One of the significant exceptions to the cardinal or basic rule of mass placement is the use of thermal mass in the exterior courtyards for cooling in summer. Thermally massive courtyard floor with a shade giving arcade provides cooling to the house. The night time radiation to the clear sky cools the mass and cool air trapped in the courtyard which is drawn into the building replacing warmer night air in the indoor. During day shading arcade protects building from direct solar heat gain and cool mass absorbs significant heat from sun.

1.3.3 ACTIVE HEATING STRATEGIES

In active heating strategies the active system uses mass to store thermal energy and use it in a later time during heating season. Appropriate sized thermal mass can manage thermal energy diurnally and seasonally which remains thermally isolated from collector and conditioned space and stores all summer heat to use it in winter.

1.4 OBJECTIVE OF THE RESESARCH

The objective of this project is to understand and quantify the benefits of integrating higher levels of thermal mass in Canadian single family dwellings for passive strategies. The work will include the following steps:

1. To review the impact of thermal mass on heating and cooling energy consumption for different types of buildings (residential facilities, single detached etc.) from previous research.
2. To investigate the impact of thermal mass on two different typical house types using Energy Plus simulation software model.
3. To compare the energy consumption of the house types for different mass weight such as light, medium and high thermal mass.

4. To compare performance of thermal mass with different envelope specifications such as high R value walls, glazing percentage and reduced U value of the window.
5. To identify the benefits of thermal mass in housing compared to other energy saving strategies as well as the demerits of using thermal mass.

2 BACKGROUND OF THERMAL MASS

Thermal mass is the capacity of a material to absorb and store heat and release this heat when it is necessary. It is measured in the number of joules of thermal energy stored per unit of mass (J/kg.K) or per cubic meter of material (J/m^3K). The basic strategy for using heavy structural elements (such as masonry walls) is its heat absorbing character for which it can store heat during the daytime and occupied periods and release the heat to the ambient air at nighttime, which is an age-old strategy for vernacular green designs for warm climates (Gorgolewski, 2007). *Mathematically, thermal mass is the product of the specific heat and density of the materials that makes a structure.* (Wong, Liyao, n. d). Use of thermal mass is usually part of a passive design strategy which promotes energy conservation and improved comfort through the use of the building form and materials to reduce energy use. (Wong, Liyao, n. d) Building envelope with high thermal mass delays the transient heat flux during day, thus smoothing the fluctuation of interior temperature (Wong, Liyao, n. d). This damping in interior air temperature contributes to better indoor temperature control and significant energy savings as the peak demand is reduced.

2.1 HEAT TRANSFER MODE OF THERMAL MASS

There are three methods of heat transfer between the mass and the environment:

- Radiation - from sun, or any other surfaces with a higher temperature
- Convection through air (fluid) movement past the surface of the mass
- Conduction with any solid materials in contact with the mass

Temperature differences usually measure the rate of heat flow through the environment which increases with larger temperature difference. Thermal mass directly exposed to the solar radiation effectively absorbs and stores significant amounts of radiant energy. Similarly mass exposed to terrestrial radiant sources (lamp, people, equipment) absorb and store large amount of radiant energy. (Haglund, Rathmann, n.d) When the temperature of the mass exceeds surrounding air and surface temperatures it will experience net conductive- convective and radiant heat loss to the surrounding surfaces and vice versa. Also mass gains heat by conduction and convection from warmer solid or fluid and release heat to cooler solid or fluid with similar heat transfer methods. This can be important during cooling cycle when it is possible to remove the heat stored in the thermal mass by flashing heat with fresh outside air through or past the mass which will then exchange heat through convection. These three heat transfer methods of thermal mass thus help cooling and heating the buildings with less mechanical heating and cooling operation.

2.2 BENEFITS OF THERMAL MASS

2.2.1 THERMAL MASS IN HEATING

High mass materials (concrete, brick, stone) can be used as wall panels, slabs, structural elements; for instance columns and beams, interior features (cabinets, staircases) or ceiling soffit etc. These high mass materials if directly exposed to the winter sun can absorb radiant heat from the sun during daytime. The concrete floor is advantageous during winter as most of the sunlight entering through windows falls on the concrete slab which can absorb and store heat in the concrete mass. Decorating materials such as tiles, slate, vinyl with good conductance can be used on top of concrete to get more thermal storage. With dark colored absorber solar energy directly absorbs in the concrete floor while light colored finishes reflect solar energy to other thermally massive surfaces such as walls or other direct gain space. While the air temperature adjacent is higher than the temperature of the mass, heat flow will be into the mass. However, the stored heat is released to the air through convection heat transfer mechanisms when the ambient air temperature is lower than thermal mass surface temperature (usually at night time). Furthermore, if the surface temperature of the mass is higher than the surface temperature of the surfaces in the same space, it will radiate heat to these other surfaces Thus thermal mass helps in space heating during night time.

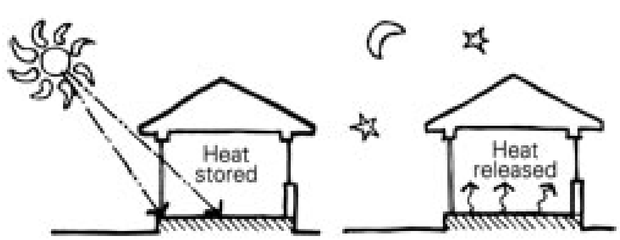

Figure 5 Thermal Mass in Winter Heating (source: http://www.yourhome.gov.au/technical/fs49.html, 2012)

It is important to note that there are several drawbacks of thermal mass. During winter months it may increase the heating energy demand due to additional heating requirement to warm the thermal mass (Gorgolewski, n.d). In the evening thermally heavy structure cool slowly if the outdoor is not in significantly lower temperature. Also in the morning it takes longer time to warm up the building.

Concrete floor slab on the ground acts as a vulnerable thermal bridge (because of concrete lower heat resistance) for the structure which contributes to significant heat loss to the ground. Therefore on the ground floor slab the edge specially the southern edge which acts as the main heat storage should be insulated from the ground (Figure 6). Also for external walls the outer face of internal masonry needs insulation for reducing thermal bridging (which may cause due to massive walls' higher conductivity) which can cause significant heat loss during winter months. These high thermal masses absorb and retain heat in the day time and release heat at night when outside temperature is lower. This process contributes to less energy consumption for space heating in wintertime

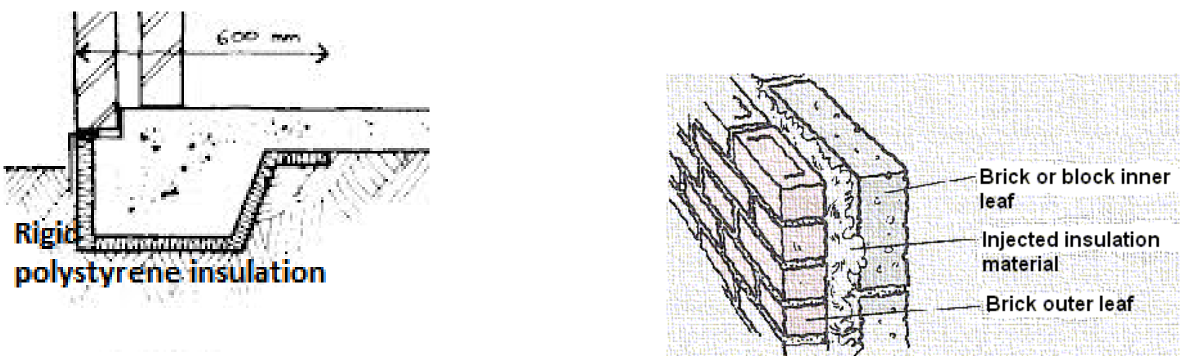

Figure 6 Slab-edge insulation in severe cold climate areas and Insulation of cavity wall (source: http://www.west-norfolk.gov.uk/default.aspx?page=22400, 2012)

2.2.2 THERMAL MASS IN COOLING

During summer high mass materials act as a large heat sink such as a concrete slab on ground, as well concrete internal walls and insulated external walls enhance heat storage capacity. The solar radiation in contact with these surfaces will be partly absorbed and stored in the material until the adjacent air and surface temperatures drop. Therefore the house reacts more slowly with outdoor temperature, thus reduce dependency on mechanical cooling for comfortable indoor temperature. For the maximum benefit good cross ventilation is required in summer cooling cycle. Because at night if the outdoor temperature is lower than temperature of the mass, air flowing through the building will carry heat from building fabrics such as walls, slab etc. This process works well in warmer climates rather than colder ones (Thermal Mass Benefits for Housing, 2010). Thus it assists in removing the heat from the mass. Solar shading, deciduous vines or adjustable fabric and metal blinds on southern windows can also protect from summer overheating during extremely hot weather and such strategies should be used together with the mass to limit overheating.

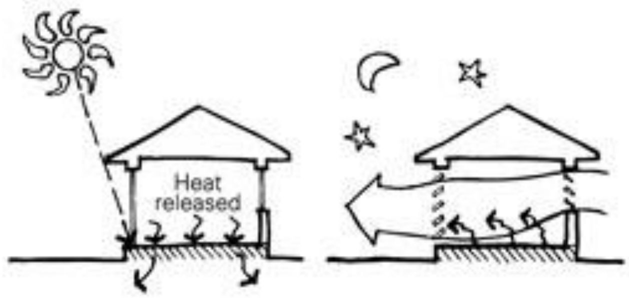

Figure 7 Concrete floor temperature modified by cool, deep-earth temperature in summer. (Source: http://www.yourhome.gov.au/technical/fs49.html)

2.2.3 TIME LAG

Massive building elements contributes to lower peak loads by storing heat in its surface; then gradually release this heat gains throughout the night time. This process reduces diurnal fluctuation in indoor temperature, thus results in more moderate heating and cooling loads. 'Time lag' represents the time delay between external maximum or minimum temperatures and internal maximum or minimum temperatures. (Figure 1 at page 12)

Time Lag can be determined by the heat transfer rate through a material or element. Low rise buildings with massive external walls can achieve approximately 10 -12 hours' time lag without the need for external insulation. However, insulation will increase the time lag by slowing the rate at which heat is lost to outside. Therefore insulation is important for massive external walls. Massive walls such as concrete block or brick walls may have less than 10 hours of time lag if the external air enter into interior earlier (than fresh air ventilation) through any leakage or unwanted cavity in the wall. In cold climates exposed external wall insulation is necessary because heating is required since adequate solar gains cannot be relied to keep overnight stable temperature. The following (Figure 8) illustrates how the indoor air temperature fluctuates in a light weight and heavy weight home. It shows temperature swings are higher in a light weight and uninsulated home (due to lack of mass and insulation) rather than a heavy weight insulated home (Baggs, Mortensen, 2006).

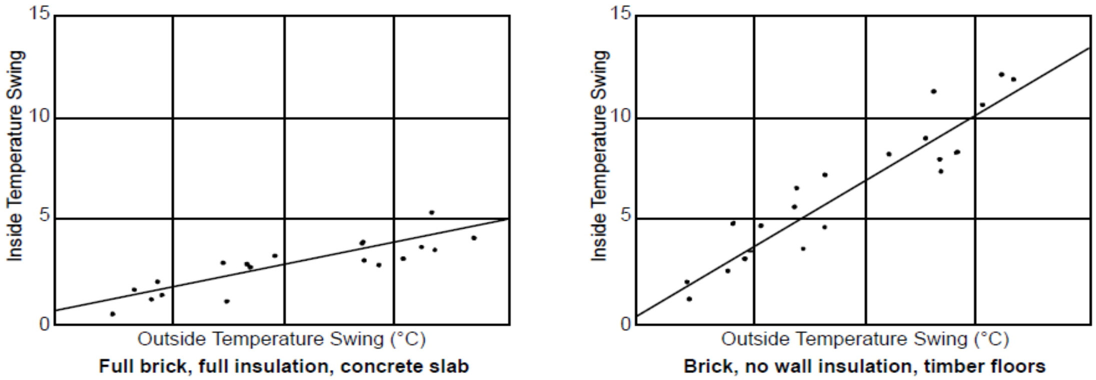

Figure 8 Comparison of temperature swing for Light weight and Heavy weight Homes. (Both X and Y axes are showing temperature swings in ^{0}C and the temperature distribution in X axis is same as Y axis) (Source: Thermal Mass in Building Design, 2006)

2.2.4 AIR TEMPERATURE VS. RADIANT TEMPERATURE

In a non- massive structure, air temperature and surface temperature of the walls, ceiling, floor and furnishing quickly become equal. When mass is used effectively, surface temperature of the mass differs significantly from air temperature and other surfaces. The difference is higher when the mass is fully charged or discharged.

Thermally massive spaces usually designed to effectively store heat gains produce higher Mean Radiant temperature (MRT). Moreover the same space if ventilated at night during cooling season, the MRT lowers. The mean radiant temperature to air temperature ratio should maintain about 1:1.5 for comfortable indoor condition (Haglund, Rathmann, n.d). Therefore in spaces influenced with thermal mass air temperature alone is not a good indicator of thermal comfort, both surface mean radiant temperature and air temperature make comfortable temperature in the indoor.

2.2.5 THERMAL MASS EFFECT ON ENERGY PERFORMANCE

Incorporation of thermal mass into the building structure not only contributes to lowering peak loads but also may save total annual space conditioning energy consumption (Energy Design Resources, 2009). Thus it helps reducing annual energy cost for space conditioning.

By lowering peak conditioning load thermal mass reduces energy consumption of the house. Therefore, the size of the HVAC system reduces which can reduce initial investment cost of the system (for smaller HVAC) comparing to the light mass construction, thus lowers initial investment of the building.

`Shifting of the peak cooling load to later time in the day can play a significant role in energy bills of the building because peak demand charges can be avoided by shifting demand from peak hours to off-peak hours which helps in reducing overall utility cost of the building(Energy Design Resources, 2009).

2.2.6 LOWER IMPLEMENTATION COST

Thermal mass is relatively less expensive (because brick, concrete, stone etc. are available in the industry and these are less expensive compared to efficient larger mechanical heating and cooling systems) passive design strategy that is easy to integrate in the building structure incorporating brick, concrete, stone and other massive elements (Energy Design Resources, 2009). Proper design of thermal mass with orientation and exposure of the building can make significant energy savings with a little increase in initial building construction cost. (Labor and other implementation cost are higher for higher thermal mass than lighter construction materials)

2.3 DESIGN CONSIDERATIONS

2.3.1 ORIENTATION

To take the maximum advantage of passive solar thermal mass buildings need orientation within about 30^0 towards south (European Concrete, n.d) during heating season and simplify shading during summer through balconies, overhangs etc.

2.3.2 LOCATING THERMAL MASS

Inside the insulated Building Envelope- For maximum benefit thermal mass should be insulated from external temperatures. It considerably reduces benefit of thermal mass if the mass is not insulated, because in the winter only thermal mass cannot provide adequate thermal resistance to the envelope, which may lead significant heat loss from the interior to the outside. For this the brick veneer wall offer less thermal mass benefit as the brick is on outside of the insulated cavity.

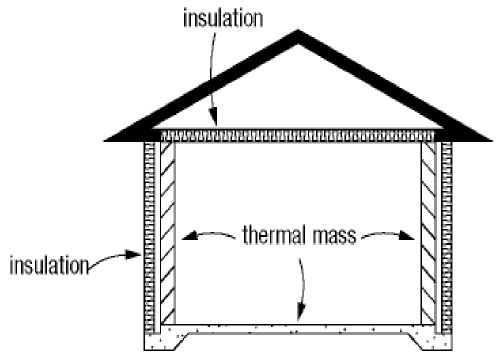

Figure 9 Thermal mass within the insulated envelope (source Sustainable energy authority, Victoria, n.d)

Concrete Slab on Ground- Concrete floor slab directly on the ground can get advantage of huge thermal mass of the earth beneath. However earth mass could be a great source heat loss for ground slab because earth has lower temperature than the slab and it is difficult to recover the heat.

Inside South Facing Room- Thermal mass in south facing room should get most priority particularly on those walls which get direct sunlight from winter sun. The more the percentage of south facing window in the house the internal thermal mass should be more to maintain stable temperatures.

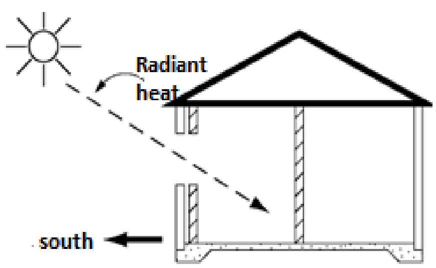

Figure 10 Thermal mass should be located in the south facing rooms (source Sustainable energy authority, Victoria, n.d)

Hot Rooms during summer -Thermal mass should be located through the house considering summer comfort particularly in the south, east and west facing rooms. It should be noted that windows in these rooms must use shading to prevent overheating from the summer sun.

2.3.3 CLIMATE

Incorporation of thermal mass is most appropriate in climates with large diurnal temperature swing. As a rule of thumb (Energy Design Resources, 2009)

- For significant energy savings usually -12^0C or more diurnal ranges are necessary.
- Depending on humidity and other factors 7^0 C to 11^0 C ranges can be useful.
- More than 7^0 C or more ranges are appropriate for high mass construction.

In arid climates where diurnal ranges are generally significant and extreme both winter heating and summer cooling are necessary. For this climate high mass construction can contribute to maintain thermal comfort by passive heating and cooling principles with adequate insulation. Thus in Canadian climate winter heating is necessary whereas some city's also require cooling during summer (Toronto). Therefore adequate thermal mass with insulation can maintain comfortable indoor using passive design strategies.

2.3.4 IMPLIMENTATION AND BUILDING INTEGRATION

If thermal mass design links to a heat source and air distribution system correctly it can improve the system performance such as concrete floor slab under radiant floor heating system can absorb excessive heat directly from the heat distribution system on the slab by convection heat transfer. Moreover it can heat the air adjacent to the slab by conduction heat transfer and release the absorbed heat in a later time when the slab is fully charged and air temperature is lower than the slab; thus it can work for stabilization of interior temperatures minimizing active space conditioning loads (Energy Design Resources, 2009). However, in the radiant heating system massive floor can create overheating by transferring heat to the interior air (due to absorbing more heat from the heat distribution system) as it is not easy to control natural heat transfer of the massive element. Moreover without a well-planned heating and cooling control design strategy energy saving benefit of thermal mass may become negative. For instance during heating season setback can cause more morning warm up if the HVAC system does not get compensation for overnight cooling of the massive elements.

2.3.5 TYPES AND AMOUNT OF THERMAL MASS

Thermal capacitance (which is the measurable physical quantity of a material that characterizes the amount of heat required to change its temperature by 1^0 K or 1^0C) of a material is related to its density, such as water that has more thermal mass than any other material. Brick, earth, stone, concrete etc. are certainly common massive materials and should be chosen based on thermal capacitance, functional performance and other factors. Following Table 2 illustrates properties of some materials that can be effective as thermal mass for their higher specific heat storage capacity (which means the heat capacity per unit mass for a material). The following table shows water has the highest thermal storage capacity rather than stone, brick or concrete which are mostly used for heavy construction.

Material	Specific heat capacity J/kg.K	Thermal conductivity (W/m.K)	Density Kg/m^3
Water	4200	0.60	1000
Stone	1000	1.8	2300
Brick	800	0.73	1700
Concrete	1000	1.13	2000
Clay bricks	1000	0.21	700
Dense concrete block	1000	1.63	2300
Gypsum plaster	1000	0.5	1300
Air crete block	1000	0.15	600
Steel	480	45	7800
Timber	1200	0.14	650
Carpet	-	0.05	-

Table 2 Properties of different thermal mass materials (Source: Greenspec, UK)**.**

2.4 SPECIAL THERMAL MASS CONSTRUCTION TYPES

2.4.1 MUD BRICK (ADOBE WALL)

Mud Brick or Adobe makes generally thick walls for homes (approximately 300 mm) which have a high thermal mass (Specific heat capacity is 1260 J/kg.K and density is 1540 kg/m^3 (AIRAH, 2000). It performs well particularly in summer when the solar heat gain can be stored in the walls. However in winter mud brick walls perform poorly because of low thermal resistance which leads to heat loss through walls. To reduce heat losses in winter it is better to install external insulation to mud brick.

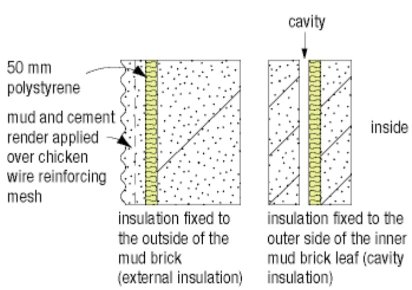

Figure 11 Insulating Mud Brick Wall (source Sustainable energy authority, Victoria, n.d)

Winter heat loss can be reduced from uninsulated mud brick walls by keeping non south windows as small as possible. South windows need to be double glazed and at least 25-30% of the floor area to help heat in winter (Sustainable energy authority, Victoria). In summer, shading is necessary for windows.

2.4.2 RAMMED EARTH

Rammed earth structures are constructed by compacting layers of earthen mixture between rigid forms which does not have high resistance (dry conductivity 0.8-1.0 W/m.K) though it has high thermal mass (Fix, Richman, 2009). Rammed earth has a broad range of dry density values varying from 1700 kg/m^3 to 2200 kg/m^3 (Maniatidis, Walker, 2003) and volumetric specific heat capacity 1673 $KJ/m^3.K$ (Thermal Mass, n.d). Rammed earth envelope can store heat from ambient air and solar radiations which combined can mitigate internal temperature fluctuations (Fix, Richman, 2009). It works better in arid and semi- arid climates however; it can reduce heating energy consumption with adequate additional insulation for cold climates. With merger R-20 insulation require 350 mm thickness of rammed earth walls in cold regions (Fix, Richman, 2009). Insulated rammed earth walls have high level of thermal resistance which improves the performance of solid rammed earth walls.

2.4.3 CONCRETE BLOCK WALL

Concrete block construction with an external insulation can increase interior thermal mass and reduce interior temperature swings. Rigid foam insulation (such as, Expanded Polystyrene, Extruded Polystyrene etc.) can be used at the outside of concrete block wall with a stucco finish. This external insulation helps reducing heat loss through concrete block and reduces energy consumption of the house. Exterior insulation system protects basement wall from damage of dam proofing or water proofing layer during backfilling (Holladay, 2012)

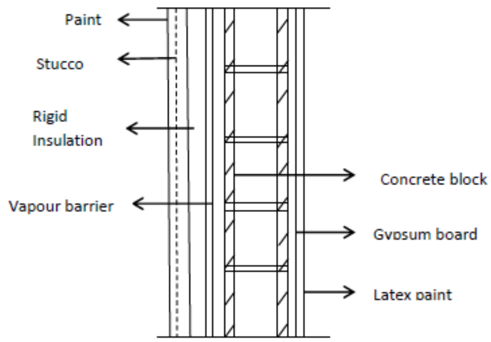

Figure 12 Concrete Block wall with Exterior insulation

2.5 SPECIAL THERMAL MASS MATERIAL

2.5.1PHASE CHANGE MATERIALS

Phase Change Material changes its state from solid to liquid to absorb heat from the outside air which in turn release this heat to the air when air temperature is lower and turn into solid state (Phase Change Materials, 2009). This property of PCM can be utilized in different ways as thermal energy storage where heat or coolness can store in one period of time and use at a later time. It is also very good in providing thermal resistance (Phase Change Materials, 2009). This property of phase change material has made it into a most important element in the building industry for heating and cooling operation. The PCM wallboard has been used as one of the thermal mass options in this research. Table 3 shows some thermophysical properties of different PCM materials.

PCM	Melting onset ^{0}C	Melting Peak ^{0} C	Thermal Conductivity W/m. K	Density Solid kg/l	Density Liquid Kg/l	Specific heat capacity KJ/kg.K
Parafin Wax	21	25	0.2	0.88	0.77	18.2
Eutectic mixture of capric-lauric acid	20	24	0.13	0.88	0.86	N/A
Eutectic mixture of capric-palmitic acid	22	26	0.14	0.88	0.84	N/A
Salt Hydrate	29	29	1.09	1.71	-	1.4

Table 3 Thermophysical Properties of different PCM 20. (Hasan A, McCormack S.J., Huang M.J., Norton B, 2010)

2.6 LITERATURE REVIEW

Balaras (1996) demonstrated thermal mass reduces peak cooling loads and temperature swings in the buildings. He also demonstrated the effectiveness of thermal mass as an energy conserving alternative for providing comfortable indoor conditions. The study shows that for climates with large diurnal temperature variations thermal mass significantly reduces energy consumption of mechanical cooling systems. He suggested designers to calculate optimum thermal mass for the facility then distribute those mass in such a way that reduces temperature fluctuation in the building. He also mentioned this system better works for office building where space can be cooled by night time ventilation for potential energy savings.

Kalogirou et al. (2002) have shown a total reduction in heating load of 47% through the application of thermal mass in a south facing wall using TRNSYS thermal simulation in Cyprus where there is large diurnal temperature fluctuations in the winter and summer. During the summer, the use of thermal mass can provide a significant improvement in the overall occupant comfort by the reducing the possibility of indoor overheating. The peak air-conditioning load which occurs during the afternoon can also be reduced by incorporating south facing walls with thermal mass. (Siddiqui, Fung, 2009)

Holford, Woods (2007) examined the role of thermal mass on a naturally ventilated building to find the interior temperature buffering from outside fluctuating temperature. They investigated the performance of thermal mass which shifts interior air temperature fluctuations. They also investigated the relation between rate of ventilation and thermal mass in maintaining interior temperature. Through the analysis and numerical solution they characterized different limiting cases. In the case of small ventilation rate thermal mass buffers the interior temperature from environmental fluctuations. In the case of rapid ventilation rate interior air temperature and thermal mass temperatures are same as environment temperature. In the case of moderate ventilation thermal mass lags fluctuations of the interior air temperature.

Wong, Liao (n.d) investigated performance of a high rise apartment building with thermal mass that did not show significant energy saving in cold climate. They used energy plus simulation for investigation with different level of thermal mass and their distribution schemes for Toronto's climatic condition. The simulation result showed reduced peak load of heating and cooling with better indoor temperature control but no significant influence on energy efficiency of the building. Kalema, Pylsy (2007) analyzed the effects of thermal mass in Nordic well insulated buildings. They compare seven calculation methods from seven researchers and seven different calculation programs (Consolis Energy, IDA-ICE, SciaQPro, TASE, VIP, VTT House model and one energy balance method for their standard (EN 832). They found that the effect of thermal mass in Nordic climate consume 3 kwh/m^2 for heating and 4 kwh/m^2 for cooling energy for weather condition of Helsinki, which has average exterior temperature of 4.6^0C and the total solar radiation of 965 kWh/m^2 on a horizontal surface with double zone TASE simulation model. They also found effect of thermal mass on cooling energy is slightly higher in apartment than single family house. Thermal mass decreases energy consumption when it is improved to extra-light building to semi-weight building. Also the study found window area and orientation with thermal mass reduces energy consumption of the apartment buildings and single family houses. Artmann, Manz, Heiselberg (2007) investigated passive cooling strategy by night-time ventilation and heat gains through sufficient amount of thermal mass in the building. They also showed the heat storage capacity of the particular building element (slab) affects maintaining thermal comfort in the building. Moreover, they investigated the impact of different parameters, such as slab thickness, material properties and the heat transfer coefficient d as well as their interrelation. The potential of increased thermal mass by using phase change materials (PCM) had been estimated in the study. The results showed d that the heat transfer coefficient has significant impact on heat storage capacity, especially for the thermally heavy elements.

Yang, Li (2008) studied a research to understanding the relationship between thermal mass and cooling load, the effect of thermal mass on energy consumption of air-conditioning in office buildings. An office building has been analyzed with air conditioning at daytime and free cooling at night time to quantify hourly and overall variation of cooling load. The analysis quantified the dependence of cooling load on thermal properties of thermal mass, convective heat transfer factors, outdoor air temperature and indoor heat gain. The result showed appropriate amount of thermal mass (with thermal properties and convective heat transfer together) with suitable outdoor climate can benefit most on energy consumption.

Zhu et. al (2008) compared the performance of an insulated exterior concrete wall system on a zero energy house over traditional wood frame system. It showed a slower temperature changes in the indoor of the massive concrete wall system. The simulated heating energy usage was much lower for the massive walls while the cooling load was a little higher because of the 24 hour high ambient climate in the area of Las Vegas, U.S.A.

Siddiqui, Fung (2009) demonstrated the detail model of net zero energy town house in Toronto developed by TRNSYS thermal simulation model, which incorporates thermal mass into the building envelope to see how it contributes to occupant comfort through reduction of indoor temperature fluctuations , also reduction of heating and cooling energy consumption. Different thermal mass, such as concrete slab, phase change material have been added to building envelope to see overall heating and cooling load in summer and winter. The result shows reduction in daily temperature fluctuations as well reduced energy consumption. The overheating problem has been addressed effectively with PCM and concrete slab integration. They also found thermal mass effectively reduce indoor air temperature deviations from the set point temperature.

Hoes, Trcka, Hensen (2011) proposed the concept of hybrid adaptable thermal storage (HATS) system and materials to a lightweight building, which increases building performance and the robustness in seasonal variations and future climate changes. The simulation results from a case study in the Netherlands showed that the minimum quantity of the thermal mass is sensitive to the change of seasons, which implies that the building performance will benefit from implementing HATS according to the study. Calculations showed the HATS concept performs 35% reduction in energy demand and better thermal comfort than conventional thermal mass concept in the building.

Kendrick, Ogden, Wang, Baiche (2012) demonstrated thermal simulation study of an UK three bedroom house to compare thermal performance of current light, medium and heavy construction techniques using Tas EDSL. The result shows thermal mass can reduce overheating during daytime. They have suggested for good design of thermal mass with good night ventilation, correct materials in the correct places. It also suggests that using ventilation and shading in occupied hours it is possible to provide thermal comfort to the occupants.

2.7 CASE STUDY

2.7.1 CONSTRUCTION

Sabins, G.M (2011) investigated the 427 m^2 (4600 ft^2) house in California Sierra Nevada foothills (where winters are cool and summer days are hot, very similar to Toronto but not as cold as Toronto) that has been constructed in 2001 using ICF walls from foundation to top plate. It is in part a living laboratory. The lower level of the house is full basement exposed to the daylight in two sides. The exterior walls of the house have used ICF walls. The walls have 6 in of flat wall, steel reinforced concrete at the core, 2.5 in of expanded polystyrene foam on each side of the concrete core, therefore thermal mass is partly insulated from the inside by polystyrene foam. At the outer cladding either fiber cement shingles or Portland cement based stucco has been used where sheet rock as the interior finish is. The composite wall exceeds thermal resistance of R-24 which may be satisfactory for California but is not a highly insulated wall for Canadian climates. However, the walls use continuous insulation with no thermal bridging other than windows and doors. The roof uses wooden truss with conventional fiber glass insulation on attic which has an R value of 36 (Sabins G.M, 2011).

The house is located at 762 m elevation, facing westward. Passive solar principles were incorporated in the design with moderate south facing window and interior hard floor surface high thermal mass. Roof overhangs and trees shade the south facing windows in summer while fully exposed to sun in winter (Sabins G.M, 2011).

2.7.2 HEATING/ COOLING PERFORMANCE

The house has been tested for wide range of weather for seven years after completion to see the performance of thermal mass. For instance, in January – February time there has been one experiment done by the owner to explore effect of thermal mass and substantial insulation. Under condition when the morning minimum temperature has been around the freezing mark and days are sunny and warming upper 10^0 C the home floats between low 15^0 to 21^0 C because of thermal mass heat release in lower temperature (Sabins G.M, 2011). The morning temperature of the house drops 17^0 C at upper level and 17^0 or 18^0 C at lower level without using any furnace or fireplace (Sabins G.M, 2011) . Summertime performance has been equally impressive. The lower level of the house does not have air conditioning and there are incidental sources of heat in the office area due to usage of numerous computers, scanners, printers, copier etc. It shows the lower level maintain a comfortable temperature of 21^0 C when outside average summer temperature has been 32^0 C (Sabins G.M, 2011).

Thus the massive house with ICF walls (though it does not have satisfactory level of insulation), massive hard floor, indoor stone fire place keep comfortable temperature in the house considering other factors; such as south face windows, tree shade at south side, roof overhangs etc. All these combined design strategies make the house comfortable.

3. METHODOLOGY

Two house types have been analyzed using Energy Plus software to assess the impact of increasing levels of thermal mass, compared to additional insulation and increased south facing windows. The two house types used are the Canadian CCHT research houses which are typical detached suburban houses, and a typical developer row house. The modeling for both was carried out for Toronto and Vancouver climates.

Energy Plus, the US Department of Energy's dynamic software for building energy simulation program contains details model of solar gain and transient flow. It is essential to capturing passive solar buildings behavior. The simulation was carried out using Canadian Weather for Energy Calculation case weather data, which is mainly based on 1953 data (Zirnhelt, Richman, n.d).

The details of the window model in Energy Plus use optical value of solar transmittance, front and rear solar reflectance and front and rear hemispherical emissivity for each individual glazing layer (Zirnhelt, Richman, n.d). Window frame divider model uses window property: Frame and Divider. It determines corresponding frame area for each window based on window dimension and frame width (Zirnhelt, Richman, n.d) . The frame edge glass conductance to center of glass conductance ratio has determined from Window 6 software (Zirnhelt, Richman, n.d). Thermal bridging is considered for all construction assemblies with windows on the above grade walls (Zirnhelt, Richman, n.d). The distribution of solar radiation model uses full exterior with reflections model. In all solar distribution model direct beam solar radiation is assumed to fall on floor only. A fraction gets absorbed by the floor and remaining fraction gets added to the diffuse radiation.

3.1 CCHT TWIN HOUSES

Twin houses at the Canadian Center for Housing Technology (CCHT) have been taken as baseline house for analysis; which are the representative of typical tract-built detached houses in Canada. These are two identical research houses and have been used for a variety of research. Their performance has been carefully monitored and Energy Plus modeling has been carefully calibrated with actual performance (Zirnhelt, Richman, n.d). Between two houses one is referred as reference house that remains unchanged as the baseline for different experiments. The experiments are carried out in the other house. These two houses are built to the R-2000 standard [1]. These two houses has been built in Ottawa in 1998 to experiment different improvement in housing technologies in the test house and compare the results with the reference house. However the modeling for this study assumed their location to be in Toronto and Vancouver.

3.1.1 DESCRIPTION OF THE HOUSE

The CCHT reference house has slight higher insulation (for CCHT attic insulation is 8.08 m^2K/W, whereas attic insulation is 6.53 m^2K/W for ASHRAE 90.1) than most of the building codes. Moreover the building is highly airtight (1.5 ACH @ 50) and has heat recovery ventilator for air circulation. For maintaining identical characteristics these houses include simulated occupants rather than real human occupants. Also they have a building automation system that turns on and off appliances, lights and hot water fixtures according to a schedule. This system represents a typical family of four people, among which two are adults and two are children. Light bulbs are used to simulate heat rejection from occupants. This automation system maintains target electricity consumption, 20 kWh/ day. For this study a calibrated Energy Plus model of the CCHT reference house (created by Hayes Zirnhelt) has been used as a reference

Feature	Value
Floor Area (Conditioned Space)	241.07 m^2
Total Window Area	35 m^2
Gross Wall area	305.39 m^2
South Facing Window Area	16.2 m^2
Window to (heat loss) wall ratio	10.93%
Window Type	Double glazed, low-e, argon filled, insulated spacer
Window Properties	SHGC = 0.52a, U = 1.63 W/m^2K
Attic R Insulation	R Value
Above Grade Wall Insulation R Value	3.19 m^2K/W ;walls with windows
Basement Interior Insulation R Value	1.82 m^2K/W
Basement Slab	75 mm concrete, un-insulated
Air tightness rating (at 50 Pa)	1.5 ACH
Gas Furnace Efficiency	80.2%
Heat Recovery Ventilator Efficiency	84%
Internal Gains	19.35 kWh/day

[1] The CCHT Twin Houses are built to the R-2000 standard, for Ottawa, however the standard is climate specific, so it may either not meet or exceed the R-2000 requirements for the other locations.((Zirnhelt, Richman,
specific, so it may either not meet or exceed the R-2000 requirements for the other locations.((Zirnhelt, Richman,
n.d)

Table 4 Key Features of CCHT house (Zirnhelt, Richman, n.d)

case of the study. The calibrated model has been made based on the infor information provided by CCHT personal M. Armstrong. Table 4 summarizes important relevant features of the CCHT house.

The architectural drawings of the house are provided in the Appendix B. The house includes a heated basement and unheated double car garage. The design includes many complex roof lines which is a common practice in North America for new constructions which is not ideal for low energy design. The as modeled house is shown in the following (Figure 13).

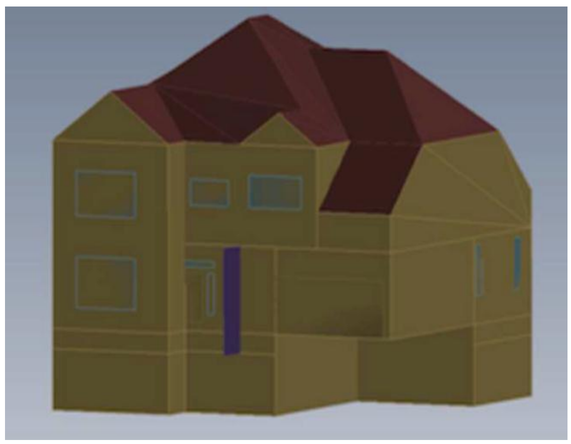

Figure 13 Model of CCHT house (Zirnhelt, Richman, n.d)

3.2 ROW HOUSE

A row house has also been modeled for investigating the impact of thermal mass. This house is assumed one of the middle houses in the row, therefore east and west walls of the house are considered indoor walls which do not exchange heat with opposite walls. In this house the heated basement is on above grade which consists of garage, mechanical room, laundry, den and store. The walls, floors and roofs follow the Ontario Building Code (OBC) 2012 (zone 1, compliance package A) requirements. The airtightness has been considered from Energy Star standard. The important relevant features of the house are mentioned in the following Table 5.

Feature	Value
Floor Area (Living Space)	225.49 m^2
Window Area	24.37 m^2
South Facing Window Area	14.60 m^2
Gross wall area	126.38 m^2
Window Type	Double glazed, low-e, argon filled, insulated spacer
Window to (heat loss) wall ratio	19.28%
Window Properties	SHGC = 0.38, U = 1.46 W/m^2K
Attic R Insulation	R Value 10.41 m^2K/W
Above Grade Wall R Value	5.61 m^2K/W
Basement Slab	0.30 m concrete, un-insulated
Air tightness rating (at 50 Pa)	3 ACH (Energy Star, 2011)
Gas Furnace Efficiency	84 %
Heat Recovery Ventilator Efficiency	55 %
Internal Gains	19.35 kWh/day

Table 5 Key Features of row house

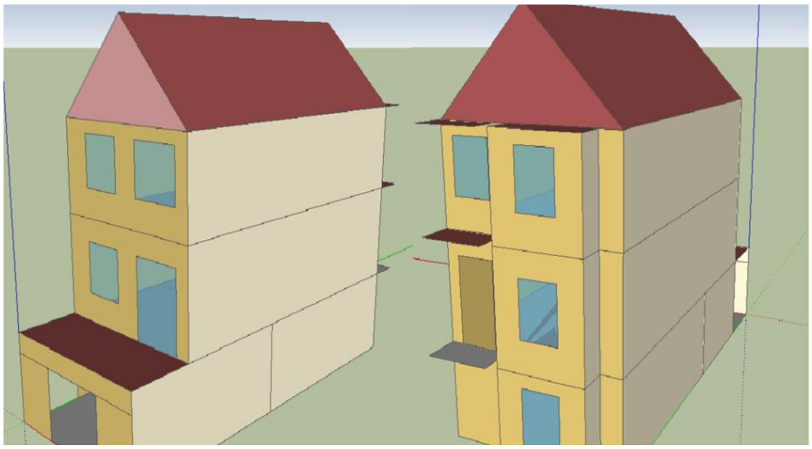

Figure 14 Model of row house

3.3 ENERGY PLUS MODELING OF CCHT AND ROW HOUSE

The houses has been modeled in the Energy Plus version 7. For the simulation run period weather has been considered Energy Plus weather data for 2002-2003 was used for annual simulations. Though the CCHT house is located in Ottawa, and the Row house is located in Toronto analyses have been done for Toronto and Vancouver location which represent two different weather conditions in Canada.

3.3.1 MATERIALS

Construction materials for the CCHT house envelope has been defined prior to the construction detail input in the Energy Plus idf editor, which require the roughness, thickness, conductivity, density and specific heat properties for recognizing a material. For both houses (CCHT and Row) 13 different materials have been created in idf editor which include brick, gypsum board, extruded polystyrene (XPS), OSB, Concrete, Tiles, Insulation for basement and upper levels, ceiling and roof exterior (asphalt shingles), air space in the wall cavity. For window glazing following inputs are required in Energy Plus. It considers glazing optical values, such as glass solar transmittance, front side solar reflectance, and back side reflectance, visible transmittance of front and back side etc. The materials properties for CCHT and row house are included in the Appendix A.

3.3.2 CONSTRUCTION

The envelope surfaces have been constructed (for CCHT and row houses), from the predefined materials which consist of different layers of materials for different envelope elements. For instance for brick wall construction of CCHT house the layers have been defined as brick for outside layer, then OSB, insulation and gypsum which in combined make an overall R value 3.19 m^2K/W. For row house the overall R value of the wall is 5.6 m^2k/W (Row house insulation thickness (0.25m) is higher than that of CCHT house 0.14m). The construction of wall and floor assembly is shown in the Figure 15.

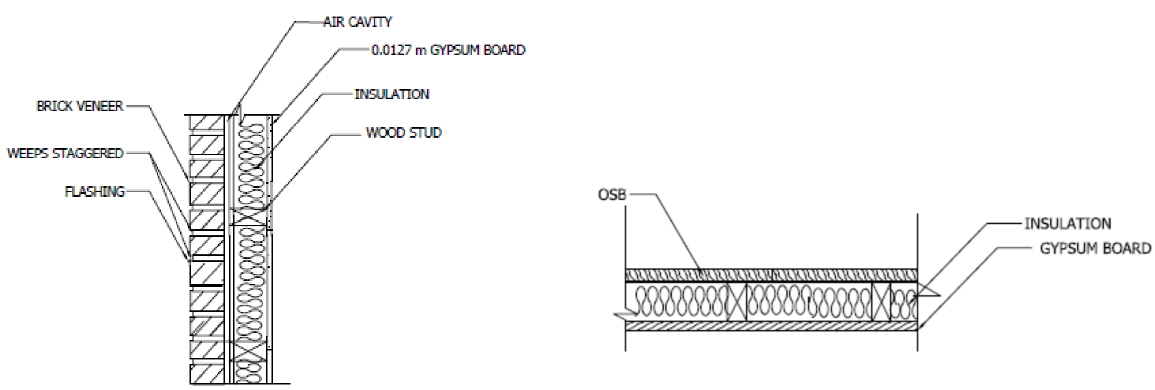

Figure 15 CCHT and Row houses wall and floor assembly details

3.3.3 BUILDING SURFACE DETAILS

In Energy Plus building geometry is defined by different walls, floors and roofs surfaces. In the building surface details section (in Energy Plus) walls, floor and roof surface geometry are described with its location (such as garage zone/ zone 1), surface type construction details and geometry with three dimensional (X, Y, and Z vertices) positions. The house has been built in this section defining all building envelope elements (both below grade and upper grade), such as walls in each side (North, south, east and west), roofs (north, south, east, west), floors and garage. This section require value for construction name, surface name, outside boundary condition, sun exposer, wind exposure and all vertices for geometry construction. These surface details create the house geometry which is being shown in Figure 13 and Figure 14.

3.3.4 SCHEDULE

For both houses different schedules have been created for the operation of mechanical and electrical equipment which are mainly based on an on/off schedule, occupancy activity and occupant availability. The schedules that have been defined in the model include heating schedule, cooling schedule, HRV operation schedule, infiltration schedule, kitchen appliances schedule, main floor and second floor lighting schedule, dining room appliances schedule, stove schedule, washing machine and dryer schedule. The schedules consider CCHT occupancy schedule (Appendix B).

3.3.5 INTERNAL GAINS

Internal gains consider for people, lights, electrical equipment and hot water equipment which are responsible for heat gains in the conditioned space of the house. Internal gains consider different watt designs for different equipment according to CCHT information. For instance, light watt levels have been considered 200 W for all main floor lights and 410 W for all 2nd floor lights as mentioned in CCHT occupancy schedule (Appendix B). The light watt levels for row house consider 9.6 W/m^2 and 6.5 W/m^2 for 2nd and 3rd floor lights from ASHRAE guidelines for residential facilities (ASHRAE 90.1) The internal gain details are included in the Appendix A.

3.3.6 HVAC SYSTEM

Energy Recovery Ventilator:

The houses have been divided into four zones for space conditioning, which include all living space (zone 1), basement zone, garage zone and attic zone. For zone 1 dual thermostat set point has considered as zone 1 heating set point and zone 1 cooling set point schedule. An energy recovery ventilator has been modeled as a HVAC equipment which follows predefined HRV schedule with 0.03 m^3/s supply and exhaust air rate. In the model of ERV three components are required, which include a generic air to air heat exchanger, supply air fan, exhaust air fan. The following Figure 16 shows the schematic picture of the ERV as zone HVAC equipment.

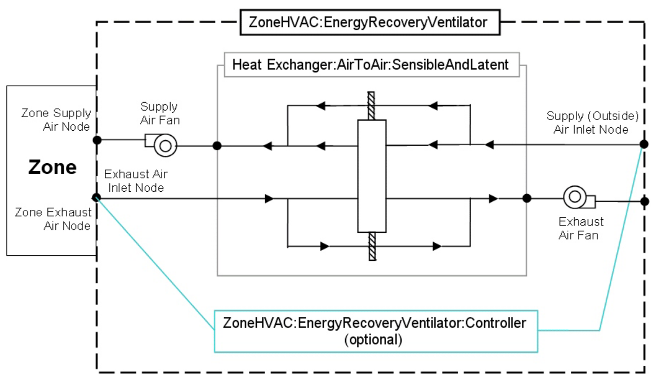

Figure 16 Zone HVAC: Energy Recovery Ventilator compound object Schematic (source: Energy Plus input/output file)

Zone HVAC Air Loop Terminal unit:

Air loop terminal considers two uncontrolled single ducts for zone 1 and basement. For two of the zones these ducts are at the supply air node with dual zone control schedule. The supply air rates for these two ducts 0.5287 m^3/s for zone 1 and 0.0933 m^3/s for basement zone.

Fans:

Three fans are operating in the HVAC equipment, one is air loop HVAC fan other two are HRV supply and exhaust fan. The flow rates for these fans include 0.68 m^3/s for furnace fan and 0.04 m^3/s for HRV fan.

Air Loop HVAC: Unitary: (Heat and Cool):

The air loop HVAC has been designed for both heating and cooling load. The coils include DX single speed cooling coil and heating gas coil which has a nominal capacity of 19778 W with 80% efficiency for CCHT house and 84% efficiency for row house. The air loop HVAC considers unitary heat cool furnace with 0.622 m^3/s supply air flow rate. The furnace configuration is considered blow through which is shown in the Figure 17 below.

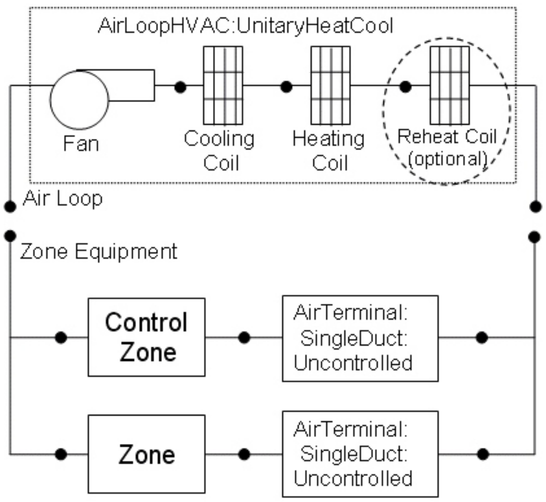

Figure 17 Schematic of Energy Plus Blow through Unitary Heat/Cool Furnace (source: Energy Plus input/output file)

3.4 MODELING OF DIFFERENT TYPE OF THERMAL MASS ON CCHT AND ROW HOUSE

The existing models for both houses have been changed partially to see the energy performance of the house for different mass incorporation. The following is a description of the way the specification was changed to increase the amount of thermal mass that was modeled.

3.4.1 CEMENT PARTICLE BOARD

The interior finishes of the walls and floors of the base house models are of gypsum (12.7mm thickness) in both houses. The first variation was to use cement particle board (12 mm thick) which has more mass than the traditional gypsum in place of gypsum drywall (Table 6), which increases the volumetric heat capacity of interior walls. However walls R value decrease to 3.15 m^2K/W for CCHT and 5.5 m^2K/W for row house. The improved wall assembly is shown in the Figure 18.

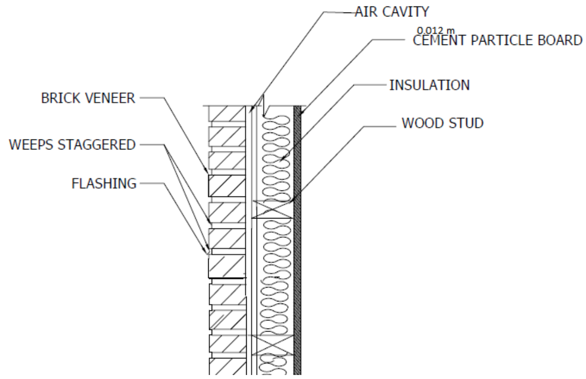

Figure 18 Improved wall assembly with 0.012 m Cement Particle Board

Incorporation of cement particle board increases the weight of the structure from 2875 kg gypsum to 5307 kg cement particle board for CCHT and 1683 kg to 3108 kg for row house. The construction details of the cement particle board wall and floor are provided in the Appendix A.

Material	Wall Area m^2	Floor Area m^2	Thickness m	Density Kg/m^3	Specific heat capacity (J/Kg.K)	Total heat capacity (MJ/K)
Gypsum (CCHT)	246.95	106.85	0.0127	640	1880	5.4
Cement Particle (CCHT)	246.95	106.85	0.012	1250	1300	6.8
Gypsum (row)	110.34	96.8	0.0127	640	1880	3.1
Cement Particle (row)	110.34	96.8	0.012	1250	1300	4.04

Table 6 Total Heat Capacity Calculation for Cement Particle Board (CCHT and row house)

3.4.2 BRICK WALL IN THE INNER LEAF

In the second trial the interior gypsum drywall (0.0127 m thick) has been improved to 0.1 m brick wall which increases the total heat capacity of the walls by 34.2 MJ/K for CCHT house and 15.2 MJ/K for row house (Table 7). R value of the walls increase to 3.2 m^2K/W for CCHT and 5.8 m^2K/W for row house. Also brick wall in the inner leaf causes weight of 47414 kg to the CCHT house and 21185 kg to the row house structure.

Material	Wall Area m^2	Thickness m	Density Kg/m^3	Specific heat capacity (J/Kg.K)	Total heat capacity (MJ/K)
Gypsum (CCHT)	246.95	0.0127	640	1880	3.7
Brick wall (CCHT)	246.95	0.1	1920	800	37.9
Gypsum (row)	110.34	0.0127	640	1880	1.7
Brick wall (row)	110.34	0.1	1920	800	16.9

Table 7 Total Heat Capacity Calculation for Brick Wall Inner Leaf (CCHT and row house)

The construction detail of the wall assembly is shown in the Figure 19.

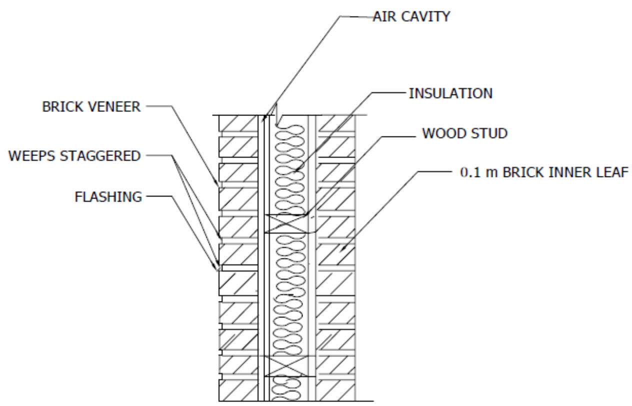

Figure 19 Details of wall assembly with 0.1 m brick wall in the inner leaf

3.4.3 CONCRETE WALL IN THE INNER LEAF

Material	Wall Area m^2	Thickness m	Density Kg/m^3	Specific heat capacity (J/Kg.K)	Total heat capacity (MJ/K)
Gypsum (CCHT)	246.95	0.0127	640	1880	3.7
Brick wall (CCHT)	246.95	0.1	2000	1000	49.3
Gypsum (row)	110.34	0.0127	640	1880	1.7
Brick wall (row)	110.34	0.1	2000	1000	22

Table 8 Total Heat Capacity Calculation for Concrete Wall Inner Leaf (CCHT and row house)

Concrete has a high thermal mass rather than brick (such as concrete density is 2000 kg/m^3 and specific heat capacity is 1000 J/kg k whereas brick has 1920 kg/m3 density and is 800 J/kg k specific heat capacity), which plays a significant role in passive heating and cooling. Therefore for this trial the inner wall has been changed to 100 mm concrete. Interior partition walls also get altered with 100 mm concrete instead of gypsum. It gives total heat capacity of the walls by 49.3

MJ/K for CCHT and 22 MJ/K for row house (Table 8). The R values of the walls remain similar as brick wall inner leaf mass. Also concrete gives 49390 kg weight to CCHT house and 22068 kg to row house. The construction detail is shown in the following Figure 20.

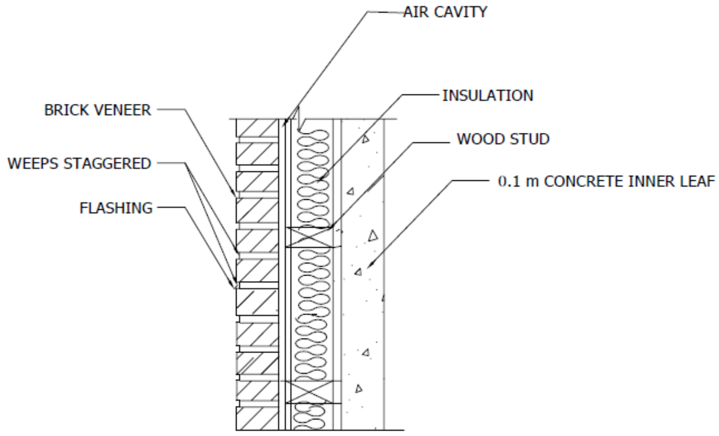

Figure 20 Details of wall assembly with 0.1 m concrete in the inner leaf

3.4.4 CONCRETE WALL AND CONCRETE FLOOR (HIGH MASS)

Material	Wall Area m^2	Floor Area m^2	Thickness M	Density Kg/m^3	Specific heat capacity (J/Kg.K)	Total heat capacity (MJ/K)
Gypsum (CCHT)	246.95	106.85	0.0127	640	1880	5.4
Concrete (CCHT)	246.95	106.85	0.1	2000	1000	70.7
Gypsum (row)	110.34	96.8	0.0127	640	1880	3.1
Concrete(row)	110.34	96.8	0.1	2000	1000	41.4

Table 9 Total Heat Capacity Calculation for Concrete Wall and Floor (High mass) (CCHT and row house)

For getting high thermal mass in the houses all walls and floors have been changed to 100 mm concrete (Table 9) in the interior. Concrete is placed inside the insulation to get the better performance. Concrete in the walls and floors give the above volumetric heat capacity for both houses. Concrete adds 70760 kg weight for CCHT and 41440 kg for row house. The wall (Figure 20) and floor details are shown in the Figure 21.

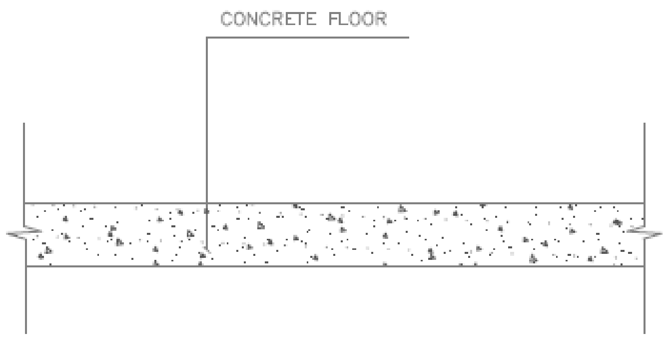

Figure 21 Floor details for 0.1 m concrete instead of gypsum

3.4.5 PHASE CHANGE MATERIAL

CCHT and row houses envelopes have been tested for phase change material (PCM). Micronal PCM wall board (Micronal PCM, 2006) has been modeled instead of gypsum board in the interior walls as well in the roof ceiling. The thickness considered for 3 of the wall board which accounts 45 mm to get more thermal mass. This board has operation temperature 23^0 to 26^0 C (Micronal PCM, 2006). If the outside temperature increases over the threshold this material absorb heat in its phase change and release this heat if temperature goes below threshold. PCM wall board adds 18.1 MJ/K total heat capacity to the interior walls for CCHT house and 6.8 MJ/K for row house (Table 10). However the wall R value increases to 3.3 m^2K/W for CCHT and 5.7 m^2K/W for row house and 8.7 m^2K/W for insulated roof in CCHT and 10.6 m^2K/W in row house.

Material	Wall Area m^2	Ceiling and roof Area m^2	Thickness M	Density Kg/m^3	Specific heat capacity (J/Kg.K)	Total heat capacity (MJ/K)
Gypsum (CCHT)	246.95	300.74	0.0127	640	1880	8.3
PCM (CCHT)	246.95	300.74	0.045	800	1341	26.4
Gypsum (row)	110.34	96.8	0.0127	640	1880	3.1
PCM(row)	110.34	96.8	0.045	800	1341	9.9

Table 10 Total Heat Capacity Calculation for Phase Change Material (CCHT and row house)

The construction details of wall assembly with PCM wall board is shown in the Figure 22.

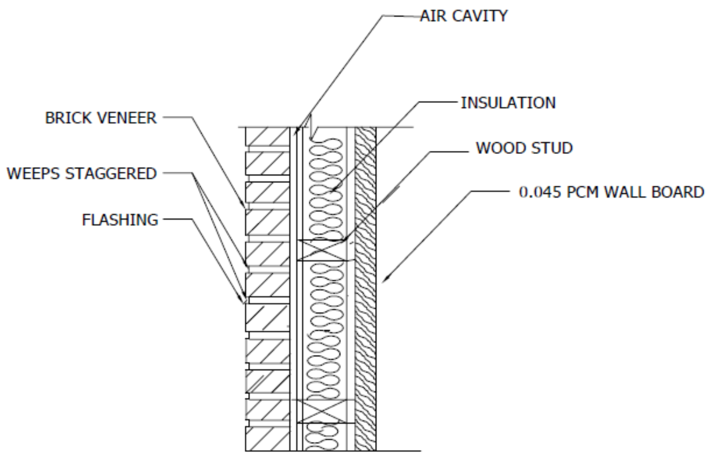

Figure 22 Details of wall assembly with 0.045 m PCM wall board.

3.5 CHANGES IN CCHT AND ROW HOUSE BUILDING ENVELOPE

The existing model has been changed partially to see the energy performance of the house for different envelope property changes. Below are the presentations of alternative specifications for walls, floors, windows etc.

3.5.1 HIGH R VALUE WALLS

The houses have also been changed to high insulation (R) values to see the performance of the house with thermal mass and insulation R value. For this the thickness of the insulation has been increased to get more R in the walls, floors and roof ceilings. It increases the R value of the existing CCHT house walls from 3.19 m^2k/W to 4.33 m^2k/W (south/north) and 3.38 m^2k/W to 4.61 m^2k/W (east/west).For row house walls R value increases from 5.61 m^2k/W to 6.6 m^2k/W. Later this trial has been tested for all the above thermal mass materials to see the performance of the R value with thermal mass incorporation. Thermal mass incorporation with increased insulation R value make negligible change to the overall R value of the wall assembly.

3.5.2 INCREASE IN GLAZING PERCENTAGE

The houses have also been tested for increased south face glazing. For this the areas of south facing windows have been increased (for CCHT house south face glazing window-wall ratio increased from 23.07% to 32.5% and for row house from 32.73% to 46.8%) without changing any other property of the window. Also two of the north windows were deleted for CCHT house to see how south facing windows perform with space heating and cooling load. South face glazing performs very well for space heating in winter where's there is problem of overheating during summer. Incorporation of thermal mass can play a significant role in this field; therefore some trials have been done with incorporation of above thermal mass elements with the increased south face glazing.

3.5.3 CHANGE IN GLAZING U VALUE

The houses have also been tested for improved thermal resistant glazing to see how heating and cooling load perform with more thermal resistance in glazing. For this triple glazing is used instead of double glazing. Triple glazing window improves U value to 1.18 W/m^2k whereas double glazing has U value 1.63 W/m^2k for CCHT house. For row house it improves U value to 1.05 W/m^2k from 1.46 W/m^2k. Also triple glazing windows have tested incorporating all above thermal masses in it such as cement particle board wall, concrete wall inner leaf, concrete wall and concrete floor (high mass) etc. The details of triple glazing window are provided in Appendix A

4. RESULTS

4.1 ENERGY PERFORMANCE COMPARISON OF EXISTING HOUSES

CCHT house shows better energy performance than average Canadian single family houses. It shows total space heating of 42.3 GJ/yr. for Toronto weather condition and 26.3 GJ/yr. for Vancouver weather. This heating energy consumption is far below the average Canadian single family dwellings heating consumption (136.5 GJ/yr.) (Zinrnhelt, Richman, n.d).The cooling energy consumption for the house is 7.8 GJ/yr. for Toronto and 6.5 GJ/yr. for Vancouver. The CCHT house has a space heating and cooling intensity of 0.18 GJ/m^2 and 0.03 GJ/m^2 for Toronto and 0.11 GJ/m^2 and 0.03 GJ/m^2 for Vancouver weather.

Row house has shown space heating energy 23.5 GJ/yr. for Toronto weather condition and 8.8 GJ/yr. for Vancouver weather, which is a good result for highly insulated envelope and airtight and window characteristics. The house consumes cooling energy 9.1 GJ/yr. for Toronto and 7.7 GJ/yr. for Vancouver. The space heating and cooling energy intensity for the house are 0.16 GJ/m^2 and 0.04 GJ/m^2 in Toronto and 0.07 GJ/m^2 and 0.02 GJ/m^2 in Vancouver.

4.2 HEATING AND COOLING ENERGY ANALYSIS

4.2.1 INCORPORATION OF THERMAL MASS FOR CCHT HOUSE

The existing CCHT house has been tested for light to high thermal mass, as well phase change materials. Incorporation of thermal mass increases volumetric heat capacity of the interior walls, floors which reduces energy consumption of the houses. The following Table 11 shows total heat capacity for different thermal mass for CCHT house.

Material	Total Heat Capacity (MJ/K)
Gypsum	5.4
Cement Particle Board	6.8
Brick Wall Inner Leaf	37.9
Concrete Wall Inner Leaf	49.3
High Mass	70.7
Phase Change Materials	26.4

Table 11 Total Heat Capacity for Different Thermal mass in CCHT house

Table 12 shows the results for heating energy and cooling energy consumption for CCHT house in Toronto weather condition. It shows thermal mass improves energy consumption of the house maximum 4.3 GJ (8.5% savings) for incorporation of 70.7 MJ/k volumetric heat capacity with concrete walls and floors mass. Concrete high mass reduces both heating (2.76 GJ) and cooling (1.54 GJ) energy of the house. However, concrete inner leaf mass reduces cooling energy maximum (2 GJ).

System	Heating Energy (GJ)	Heating Energy Reduction (GJ)	Cooling Energy (GJ)	Cooling energy reduction/increase (GJ)	Total Energy (GJ)	Total Energy reduction (GJ)
Existing Twin House	42.3		7.8		50.1	
Cement Particle Board Thermal Mass	41.3	0.9(2.1%)	7.4	0.3 (3.8%)	48.8	1.3 (2.5%)
Brick Wall Inner Leaf	40.6	1.6 (3.7%)	6.3	1.4 (17.9%)	47.07	3.1 (6.1%)
Concrete Wall Inner Leaf	40.1	2.1(4.9%)	5.8	2 (25.6%)	46.01	4.1 (8.1%)
High Thermal Mass	39.5	2.7(6.3%)	6.3	1.5 (19.2%)	45.8	4.3 (8.5%)
Phase Change Material	39.6	2.6 (6.1%)	6.7	1.08 (13.8%)	46.4	3.7 (7.3%)

Table 12 Sensible Heating and Cooling Energy for CCHT house (Toronto Weather Condition)

For Vancouver weather energy consumption of the house is lower than Toronto. The CCHT house consumes 32.9 GJ energy for space conditioning, which gradually reduces for more thermal mass incorporation. Concrete high mass reduces both heating (2.94 GJ) and cooling (2.22 GJ) energy which accounts maximum 5.16 GJ (15.6% savings) of energy reduction (Table 13). However maximum cooling energy reduced for concrete inner leaf mass by 2.56 GJ.

PCM wall board reduces less energy than concrete high mass as PCM is used in the wall board which has a volumetric heat capacity lower than concrete. PCM in concrete would show better performance than wall board.

System	Heating Energy (GJ)	Heating Energy Reduction (GJ)	Cooling Energy (GJ)	Cooling energy reduction/increase (GJ)	Total Energy (GJ)	Total Energy reduction (GJ)
Existing Twin House	26.3	-	6.5	-	32.9	
Cement Particle Board Thermal Mass	25.2	1.08 (4.1%)	6	0.5 (7.7%)	31.2	1.6 (4.8%)
Brick Wall Inner Leaf	24.6	1.7 (6.4%)	4.9	1.6 (24.6%)	29.5	3.3 (10%)
Concrete Wall Inner Leaf	24.01	2.3(8.7%)	4	2.5 (38.4%)	28.01	4.9 (14.8%)
High Thermal Mass	23.4	2.9 (11%)	4.3	2.2 (33.8%)	27.7	5.1 (15.5%)
Phase Change Material	24	2.3 (8.7%)	5.3	1.2 (18.4%)	29.3	3.5 (10.6%)

Table 13 Sensible Heating and Cooling Energy Consumption for CCHT house (Vancouver Weather Condition)

4.2.2 INCORPORATION OF THERMAL MASS FOR ROW HOUSE

For the row house total energy consumption is lower (32.6 GJ for Toronto and 16.5 GJ for Vancouver) than CCHT house for both weather conditions. However, cooling energy consumption of the row house (9.1 GJ for Toronto and 7.7 GJ for Vancouver) is more than CCHT house (7.84 GJ for Toronto and 6.56 for Vancouver) which is due to east and west walls (which does not allow heat loss through the walls). These two walls are the partition walls of the middle row house. Thermal mass incorporation gradually reduces energy consumption of the house. Different thermal mass incorporates total heat capacity to the walls, floors etc.

Materials	Total Heat Capacity (MJ/K)
Gypsum	3.1
Cement Particle Board	4.04
Brick wall inner leaf	16.9
Concrete wall inner leaf	22
High mass	41.4
Phase Change Material	9.9

Table 14 Total Heat Capacity For Different Thermal mass in row house

Table 15 shows high thermal mass reduces both heating (1.1 GJ) and cooling (0.7GJ) energy which account maximum energy reduction of 1.8 GJ (5.5% savings) for Toronto for row house.

High mass incorporate maximum 41.4 MJ/K volumetric heat capacity. Moreover, for row house brick and concrete inner leaf walls show similar energy consumption though concrete increases 5.1 MJ/K volumetric heat capacity than brick.

System	Heating Energy (GJ)	Heating Energy Reduction (GJ)	Cooling Energy (GJ)	Cooling energy reduction/increase (GJ)	Total Energy (GJ)	Total Energy reduction (GJ)
Existing Row House	23.5		9.1		32.6	
Cement Particle Board Thermal Mass	23.3	0.2 (.85%)	8.9	0.2 (2.2%)	32.2	0.4 (1.2%)
Brick Wall Inner Leaf	22.6	0.9 (3.8%)	8.61	0.5 (5.4%)	31.2	1.4 (4.3%)
Concrete Wall Inner Leaf	22.6	0.9 (3.8%)	8.6	0.5 (5.4%)	31.2	1.4 (4.3%)
High Thermal Mass	22.4	1.1 (4.6%)	8.3	0.7 (7.6%)	30.7	1.8 (5.5%)
Phase Change Material	23	0.5 (2.1%)	8.8	0.3 (3.3%)	31.8	0.8 (2.5%)

Table 15 Sensible Heating and Cooling Energy for Row House (Toronto Weather Condition)

In Vancouver weather condition heating energy consumption of the house is very lower than Toronto (14.7 GJ less) whereas cooling energy consumption is only 1.4 GJ less. The house shows similar pattern of energy reduction for different thermal mass incorporation in Vancouver. The heating (1 GJ) and cooling (0.7 GJ)) energy reduces maximum for high mass which accounts a maximum 1.7 GJ (10.3% savings) energy reduction. Table 16 shows the results for thermal mass incorporation in the row house for Vancouver.

System	Heating Energy (GJ)	Heating Energy Reduction (GJ)	Cooling Energy (GJ)	Cooling energy reduction/increase (GJ)	Total Energy (GJ)	Total Energy reduction (GJ)
Existing Row House	8.8		7.7		16.5	
Cement Particle Board Thermal Mass	8.6	0.2 (2.3%)	7.5	0.2 (2.6%)	16.1	0.4 (2.4%)
Brick Wall Inner Leaf	8.1	0.7 (7.9%)	7.2	0.4 (5.2%)	15.3	0.9 (5.4%)
Concrete Wall Inner Leaf	8	0.8 (9%)	7.1	0.5 (6.5%)	15.1	1.3 (7.8%)
High Thermal Mass	7.8	1 (11.3%)	6.9	0.7 (9%)	14.7	1.7 (10.3%)
Phase Change Material	8.3	0.5 (5.6%)	7.4	0.3 (3.9%)	15.7	0.8 (4.8%)

Table 16 Sensible Heating and Cooling Energy for Row House (Vancouver Weather)

4.2.3 HIGH R VALUE AND THERMAL MASS FOR CCHT HOUSE

Increasing the insulation in the wall assembly reduces heating energy to a great extent due to thermal resistance of the insulation material which increases a little cooling energy in the house. Insulation material does not increase volumetric heat capacity of wall as its density is very lower than thermal mass material. Therefore adding insulation is easier than thermal mass incorporation.

In the CCHT house wall and ceiling insulation makes a 0.94 MJ/K volumetric heat capacity with a weight of 1117.6 kg. Increasing the insulation over wall and roof increases volumetric heat capacity to 1.24 MJ/K. Table 17 shows in Toronto high R value wall and ceiling insulation reduces heating energy 7.1 GJ and increase cooling energy 0.5 GJ which accounts 6.6 GJ (13.2% savings) of energy reduction, which shows improved performance than thermal mass. However, thermal mass can better the performance of energy consumption with high insulation value. The energy reduction for the high mass high R value walls is 10.8 GJ (21.5% savings) which is significant energy reduction of CCHT house in Toronto weather condition. However concrete inner leaf wall also reduces 10.7 GJ total energy in Toronto.

System	Heating Energy (GJ)	Heating Energy Reduction (GJ)	Cooling Energy (GJ)	Cooling energy reduction/increase (GJ)	Total Energy (GJ)	Total Energy Reduction (GJ)
Existing Twin House	42.3		7.8		50.1	
High R Value	35.2	7.1(16.7%)	8.3	-0.5 (-6.4%)	43.5	6.6 (13.2%)
Cement Particle Board With High R Value	34.1	8.2 (19.3%)	8.03	-0.23 (-2.9%)	42.1	8 (15.9%)
Concrete Wall With High R Value	33.1	9.2 (21.7%)	6.3	1.5 (19.2%)	39.4	10.7 (21.4%)
High Thermal Mass With High R Value	32.5	9.8 (23.1%)	6.8	1 (12.8%)	39.3	10.8 (21.5%)

Table 17 Sensible Heating and Cooling Energy for Row House with High R value and Thermal Mass (Toronto Weather)

In Vancouver weather high R value wall and roof reduces 5.02 GJ heating and increase 0.8 GJ cooling energy which in total reduce 4.2 GJ (12.7% savings) of energy, which is improved than thermal mass performance in Vancouver. High mass with high R value walls reduces 9 GJ (27.3% savings) total energy with 7.2 GJ heating and 1.16 GJ cooling energy reductions. Moreover concrete walls in the inner leaf mass shows improved performance (26.8% savings) for Vancouver too. Table 18 shows the results for CCHT house with high R walls and thermal mass in Vancouver weather.

System	Heating Energy (GJ)	Heating Energy Reduction (GJ)	Cooling Energy (GJ)	Cooling energy reduction/increase (GJ)	Total Energy (GJ)	Total Energy Reduction (GJ)
Existing Twin House	26.3	-	6.5	-	32.9	
High R Value	21.3	5.02 (19%)	7.4	-0.8 (-12.3%)	28.7	4.2 (12.7%)
Cement Particle Board With High R Value	20.2	6.1 (23.2%)	6.9	-0.4 (-6.2%)	27.2	5.7(17.3%)
Concrete Wall With High R Value	19.1	7.2 (27.3%)	4.9	1.16 (17.8%)	24.1	8.8 (26.8%)
High Thermal Mass With High R Value	18.5	7.8 (29.6%)	5.4	1.1 (16.9%)	23.9	9 (27.3%)

Table 18 Sensible Heating and Cooling Energy for High R walls and Ceilings with Thermal Mass in CCHT House (Vancouver Weather)

4.2.4 HIGH R VALUE WALL AND THERMAL MASS FOR ROW HOUSE

For the row house increased insulation in the wall assembly increases volumetric heating capacity to 0.8 MJ/K from 0.5 MJ/K for existing house, which increases insulation from 636 kg to 834 kg. The heating energy reduces 0.8GJ and cooling energy increases 0.15 GJ for Toronto which accounts 0.65 GJ energy reductions. Whereas high mass with high R value walls reduce maximum 2.6 GJ (8% savings) energy with heating (1.9 GJ) and cooling energy (0.6 GJ) reduction in Toronto weather.

System	Heating Energy (GJ)	Heating Energy Reduction (GJ)	Cooling Energy (GJ)	Cooling energy reduction/increase (GJ)	Total Energy (GJ)	Total Energy Reduction (GJ)
Existing Row House	23.5		9.1		32.6	
High R Value	22.7	0.8 (3.4%)	9.2	-0.15 (-1.6%)	31.9	0.65 (2%)
Cement Particle Board With High R Value	22.6	0.9 (3.8%)	9.1	0.0	31.7	0.9 (2.8%)
Concrete Wall With High R Value	21.9	1.6 (6.8%)	8.7	0.4 (4.3%)	30.6	2 (6.1%)
High Thermal Mass With High R Value	21.6	1.9 (8%)	8.4	0.6 (6.5%)	30	2.6 (8%)

Table 19 Sensible Heating and Cooling Energy for High R value walls and Thermal Mass in Row House.

(Toronto Weather)

In Vancouver weather row house reduces total 0.3 GJ energy with 0.5 GJ heating energy reductions and 0.2 GJ cooling energy increase. Whereas concrete high mass wall and floor with high insulation walls and ceilings reduce energy consumption to a maximum 1.9 GJ (11.5% Savings) with 1.4 GJ heating and 0.5 GJ cooling energy reduction. Table 20 shows results for high R walls with thermal mass in row house for Vancouver weather.

System	Heating Energy (GJ)	Heating Energy Reduction (GJ)	Cooling Energy (GJ)	Cooling energy reduction/increase (GJ)	Total Energy (GJ)	Total Energy Reduction (GJ)
Existing Row House	8.8		7.7		16.5	
High R Value	8.3	0.5 (5.6%)	7.9	-0.2 (2.5%)	16.2	0.3(1.8%)
Cement Particle Board With High R Value	8.1	0.7 (7.9%)	7.7	0	15.8	0.7 (4.2%)
Concrete Wall With High R Value	7.6	1.2(13.6%)	7.4	0.3 (3.9%)	15	1.5(9%)
High Thermal Mass With High R Value	7.4	1.4 (15.9%)	7.2	0.5 (6.5%)	14.6	1.9 (11.5%)

Table 20 Sensible Heating and Cooling Energy with High R value Walls and Thermal Mass for Row House (Vancouver Weather)

4.2.5 INCREASE IN SOUTH FACE GLAZING PERCENTAGE AND THERMAL MASS FOR CCHT HOUSE

Increase in south face glazing benefits winter heating load of the houses, however in summer the house gets overheated due to summer sun. Adding overhangs or shading on the window can help from overheating.

In the CCHT house increase in the south face glazing percentage reduces heating load by 2.2 GJ and increase cooling load 3 GJ which in total increase energy consumption 0.8 GJ (1.6% increase) in Toronto. Thermal mass in the walls could benefit energy consumption by absorbing heat in it. CCHT house shows maximum 5.7 GJ (11.3% savings) energy reduction with concrete high mass for Toronto location, which reduces heating load by 6.2 GJ and increase cooling load 0.5 GJ. Moreover, concrete wall mass in the inner leaf reduces 5.5 GJ (10.9% savings) energy consumption without any increase in the cooling energy, which reflects moderate thermal mass in the walls reduces energy consumption when it is incorporated with increased south face glazing. Table 21 shows results for increased south face glazing and thermal mass for Toronto location.

System	Heating Energy (GJ)	Heating Energy Reduction (GJ)	Cooling Energy (GJ)	Cooling energy reduction/increase (GJ)	Total Energy (GJ)	Total Energy Reduction (GJ)
Existing Twin House	42.3		7.8		50.1	
More South Glazing	40.06	2.2 (5.2%)	10.8	-3 (-38.4%)	50.8	-0.8 (-1.5%)
More South Glazing With Cement Particle Board	38.5	3.8 (8.9%)	10.1	-2.3 (-29.4%)	48.7	1.5 (2.9%)
More South Glazing With Concrete Wall Thermal Mass	36.8	5.5(13%)	7.8	0	44.6	5.5 (10.9%)
More South Glazing With High Thermal Mass	36.1	6.2 (14.6%)	8.3	-0.5 (-6.4%)	44.4	5.7 (11.3%)

Table 21 Sensible Heating and Cooling Energy for Increased south face glazing and thermal mass in CCHT house (Toronto Weather)

For Vancouver CCHT house increases energy consumption 2.9 GJ (8.8% increase) for increased south face glazing which is greater than Toronto. Because Vancouver has more cooling degree days than Toronto. Also thermal mass shows similar performance as of Toronto. High concrete mass reduces maximum 4.9 GJ (14.9% savings) energy with 5.3 GJ heating energy reductions and 0.4 GJ cooling energy increment (Table 22). Whereas concrete wall inner leaf mass reduces 4.7 GJ energy with 4.73 GJ heating energy reduction and 0.02 GJ cooling energy increment.

System	Heating Energy (GJ)	Heating Energy Reduction (GJ)	Cooling Energy (GJ)	Cooling energy reduction/increase (GJ)	Total Energy (GJ)	Total Energy Reduction (GJ)
Existing Twin House	26.3	-	6.5	-	32.9	
More South Glazing	25.19	1.16 (4.4%)	10.6	-4.06 (-62%)	35.8	-2.9 (-8.8%)
More South Glazing With Cement Particle Board	23.6	2.75 (10.4%)	9.4	-2.8 (-43%)	33	-0.09 (-.3%)
More South Glazing With Concrete Wall Thermal Mass	21.6	4.73 (17.9%)	6.58	-0.02 (-0.31%)	28.2	4.7 (14.2%)
More South Glazing With High Thermal Mass	20.9	5.3 (20.1%)	6.9	-0.4 (-6.1%)	27.9	4.9 (14.9%)

Table 22 Sensible Heating and cooling energy with increased south face glazing and thermal mass in CCHT house. (Vancouver Weather)

4.2.6 INCREASE IN SOUTH FACE GLAZING PERCENTAGE AND THERMAL MASS FOR ROW HOUSE

Row house increases 1.1 GJ (3.3% increase) total energy for increased south face glazing for Toronto because it has more window-wall ratio in south side than CCHT house, moreover it has two walls in the east and west side which do not allow heat transfer. Therefore cooling energy increases more in the row house. For the row house high concrete mass reduces maximum 0.8 GJ energy (1.8 GJ heating reduction, 0.96 GJ cooling increase) energy which saves 2.5% from the existing house in Toronto location. (Table 23)

System	Heating Energy (GJ)	Heating Energy Reduction (GJ)	Cooling Energy (GJ)	Cooling energy reduction/increase (GJ)	Total Energy (GJ)	Total Energy Reduction (GJ)
Existing Row House	23.5		9.1		32.6	
More South Glazing	22.8	0.7 (3%)	11	-1.86 (-20.4%)	33.8	-1.1 (-3.3%)
More South Glazing With Cement Particle Board	23.1	0.4 (1.7%)	10.9	-1.76 (-19.3%)	34	-1.3 (-3.9%)
More South Glazing With Concrete Wall Thermal Mass	22.1	1.4(5.9%)	10.3	-1.16 (-12.7%)	32.4	0.2(0.61%)
More South Glazing With High Thermal Mass	21.7	1.8 (7.6%)	10.1	-0.96 (-10.5%)	31.8	0.8 (2.5%)

Table 23 Sensible Heating and Cooling Energy with increased south face glazing and thermal mass in Row House (Toronto Weather)

For Vancouver energy consumption increases 2.1 GJ (12.7% increase) for increased south face glazing. Which is very significant amount comparing to Toronto (3.3 % increase) because of Vancouver weather (summer temperature is greater in Vancouver). Incorporation of thermal mass in the smaller row house does not significantly reduce energy consumption even though for concrete high mass (0.1 GJ energy increment with high mass and increased south face glazing). However, thermal mass reduces energy consumption comparing the increased south face glazing energy consumption. Table 24 shows results for heating and cooling energy consumption of the row house with increased south face glazing and thermal mass for Vancouver location.

System	Heating Energy (GJ)	Heating Energy Reduction (GJ)	Cooling Energy (GJ)	Cooling energy reduction/increase (GJ)	Total Energy (GJ)	Total Energy Reduction (GJ)
Existing Row House	8.8		7.7		16.5	
More South Glazing	8.6	0.23(2.6%)	10	-2.3 (-29.8%)	18.6	-2.1 (-12.7%)
More South Glazing With Cement Particle Board	8.6	0.23 (2.6%)	9.8	-2.12 (-27.2%)	18.4	-1.8 (-10.9%)
More South Glazing With Concrete Wall Thermal Mass	7.9	0.93 (10.5%)	9.2	-1.5 (-19.4%)	17.1	-0.6 (-3.6%)
More South Glazing With High Thermal Mass	7.6	1.2 (13.6%)	9	-1.3 (-16.8%)	16.6	-0.1(-.60%)

Table 24 Sensible Heating and Cooling energy consumption with increased south face glazing and Thermal mass in Row House (Vancouver Weather)

4.2.7 REDUCED GLAZING U VALUE AND THERMAL MASS FOR CCHT HOUSE

Windows are the most vulnerable part in the building causes heat loss through glazing and frames which creates thermal bridging to the outdoor air. Therefore increase in the low e argon filled glazing reduces window U value which reduces heat loss through windows. Therefore improve in window from double glaze to triple glaze window reduces energy 2.9 GJ (5.8% savings) for CCHT house in Toronto location. Moreover, thermal mass with more thermal resistant window reduces energy consumption by 6.7 GJ (4.3 GJ heating energy reductions and 2.4 GJ cooling energy reductions) maximum for high concrete mass (Table 25), which is 13.3% total savings than existing CCHT house.

System	Heating Energy (GJ)	Heating Energy Reduction (GJ)	Cooling Energy (GJ)	Cooling energy reduction (GJ)	Total Energy (GJ)	Total Energy Reduction (GJ)
Existing Twin House	42.3		7.8		50.1	
Reduced Glazing U Value	40.5	1.8 (4.2%)	6.7	1.1 (14.1%)	47.2	2.9 (5.8%)
Reduced Glazing U Value With Cement Particle Board	39.7	2.6 (6.1%)	6.4	1.4 (17.9%)	46.1	4 (7.9%)
Reduced Glazing U Value With Concrete Wall Thermal Mass	38.6	3.7 (8.7%)	5.04	2.7 (34.6%)	43.7	6.4 (12.7%)
Reduced Glazing U Value With High Thermal Mass	38.0	4.3 (10.1%)	5.4	2.4 (30.7%)	43.5	6.7 (13.3%)

Table 25 Sensible Heating and Cooling Energy for reduced glazing U value and thermal mass in CCHT house (Toronto Weather)

For Vancouver location improved triple glazing windows show 2.4 GJ (7.3% savings) overall energy reduction with 1.3 GJ (5% savings) heating energy and 1.1 GJ (17% savings) cooling energy reduction. Whereas incorporation of thermal mass reduces maximum 6.8 GJ (20% savings) total energy with 3.9 GJ heating and 2.9 GJ cooling energy reductions (Table 26). Concrete inner leaf mass also shows significant energy reduction (6.6 GJ) comparing the added concrete floor weight to the structure for high thermal mass.

System	Heating Energy (GJ)	Heating Energy Reduction (GJ)	Cooling Energy (GJ)	Cooling energy reduction (GJ)	Total Energy (GJ)	Total Energy Reduction (GJ)
Existing Twin House	26.3	-	6.5	-	32.9	
Reduced Glazing U Value	25.02	1.3(4.9%)	5.4	1.1(16.9%)	30.4	2.4(7.2%)
Reduced Glazing U Value With Cement Particle Board	24.1	2.2 (8.3%)	4.9	1.5(23%)	29.1	3.8(11.5%)
Reduced Glazing U Value With Concrete Wall Thermal Mass	23.01	3.3(12.5%)	3.3	3.2(49.2%)	26.3	6.6(20%)
Reduced Glazing U Value With High Thermal Mass	22.3	3.9(14.8%)	3.6	2.9 (44.6%)	26.03	6.8(20.6%)

Table 26 Sensible heating and cooling energy with reduced glazing U value and thermal mass in CCHT house (Vancouver weather)

4.2.8 REDUCED GLAZING U VALUE AND THERMAL MASS FOR ROW HOUSE

In the row house improved triple glazing reduces over all energy consumption 1.7 GJ (5.2% savings) with 1 GJ (4.2% savings) heating and 0.7 GJ (7.6% savings) cooling energy reduction for Toronto location. For CCHT house (5.8% savings) % energy reduction is similar to row house. High thermal mass reduces the energy consumption to maximum 3.3 GJ (10.1% savings), which is around more 5% savings than impreoved glazing savings (Table 27)

System	Heating Energy (GJ)	Heating Energy Reduction (GJ)	Cooling Energy (GJ)	Cooling energy reduction (GJ)	Total Energy (GJ)	Total Energy Reduction (GJ)
Existing Row House	23.5		9.1		32.6	
Reduced Glazing U Value	22.5	1(4.2%)	8.3	0.7(7.6%)	30.8	1.7(5.2%)
Reduced Glazing U Value With Cement Particle Board	22.5	1(4.2%)	8.2	0.8(8.7%)	30.7	1.8(5.5%)
Reduced Glazing U Value With Concrete Wall Thermal Mass	21.8	1.7(7.2%)	8.01	1.1(12%)	29.8	2.8(8.5%)
Reduced Glazing U Value With High Thermal Mass	21.5	2(8.5%)	7.7	1.3(14.2%)	29.2	3.3(10.1%)

Table 27 Sensible Heating and Cooling Energy with reduced glazing U value and thermal mass for Row House (Toronto Weather)

For Vancouver location row house reduces 1.2 GJ (7.2% savings) overall energy for triple glazed windows with 0.6 GJ heating and cooling energy reduction. Incorporation of thermal mass reduces energy consumption up to maximum 2.7 GJ (16.3% savings) (1.5 GJ heating and 1.2 GJ cooling energy reduction) for high concrete mass.

System	Heating Energy (GJ)	Heating Energy Reduction (GJ)	Cooling Energy (GJ)	Cooling energy reduction (GJ)	Total Energy (GJ)	Total Energy Reduction (GJ)
Existing Row House	8.8		7.7		16.5	
Reduced Glazing U Value	8.2	0.6 (6.8%)	7.1	0.6 (7.7%)	15.2	1.2(7.2%)
Reduced Glazing U Value With Cement Particle Board	8	0.8 (9%)	6.8	0.8(10.3%)	14.8	1.6(9.6%)
Reduced Glazing U Value With Concrete Wall Thermal Mass	7.5	1.3(14.7%)	6.7	1(12.9%)	14.2	2.3(13.9%)
Reduced Glazing U Value With High Thermal Mass	7.3	1.5 (17%)	6.4	1.2(15.5%)	13.7	2.7 (16.3%)

Table 28 Sensible Heating and cooling energy consumption with reduced glazing U value and thermal mass for Row house (Vancouver Weather)

4.3 COMPARISON OF INDOOR TEMPERATURE

Thermal mass plays an important role in reducing indoor air temperature fluctuation through heat absorption and release that heat in a later time. For this study in the CCHT house thermostat heating set point has been set 21^0 C with always on schedule in the winter. The result shows (Figure 24) that existing house interior temperature increases more in day time due to heating from winter sun and reduces at the night time to temperature set point. Whereas for high thermal mass indoor temperature increases very little in the daytime though winter sun is heating the house, therefore indoor temperature fluctuates less even though diurnal temperature outside fluctuates in the winter . Thus thermal mass maintains thermal comfort in the house with less HVAC operation.

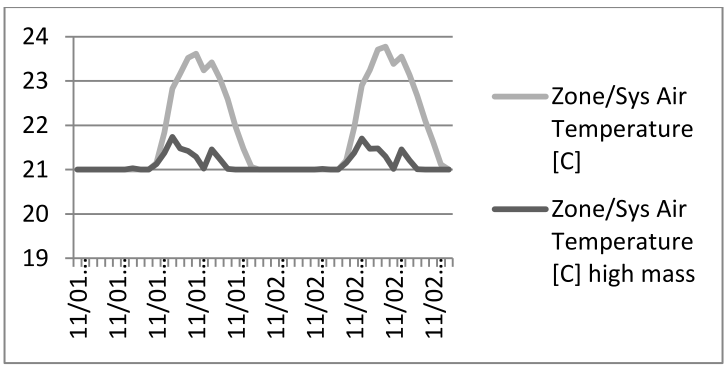

Figure 23 Comparison of indoor air temperature for existing house and high thermal mass incorporation in CCHT house (winter)

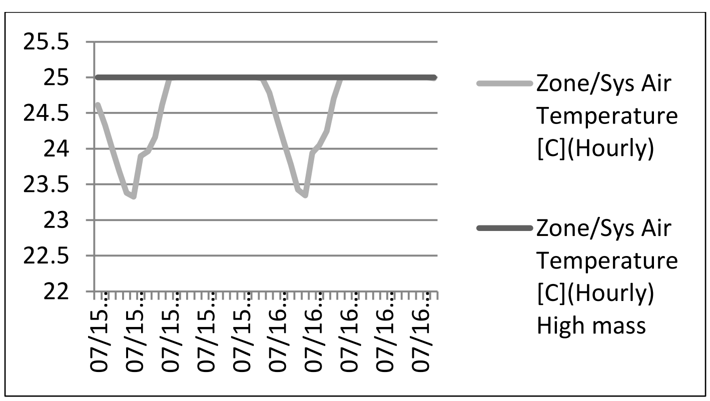

Figure 24 Comparison of indoor air temperature for existing house and high thermal mass incorporation in CCHT house (summer)

In summer the CCHT house maintains summer cooling temperature to 25^0 C with always on HVAC schedule. Therefore in summer the existing house maintains set point temperature with summer sun and reduces temperature at night time. This causes HVAC operation more at the night time. In high thermal mass condition the CCHT house maintains overall set point temperature through the day and night time which makes the indoor comfortable with less HVAC operation. (Figure 23)

In the row house winter temperature in the indoor gets higher than set point temperature (20^{0} C) for existing condition in the day time whereas concrete high mass damps the indoor temperature to lower and keep the house comfortable in winter days. Also high mass maintains stable temperature at night time (Figure 25). In summer high mass maintains stable set point temperature (26^{0} C) through the day and night time whereas existing house reduces indoor temperature to lower in the morning, which shows fluctuations in the summer temperature.

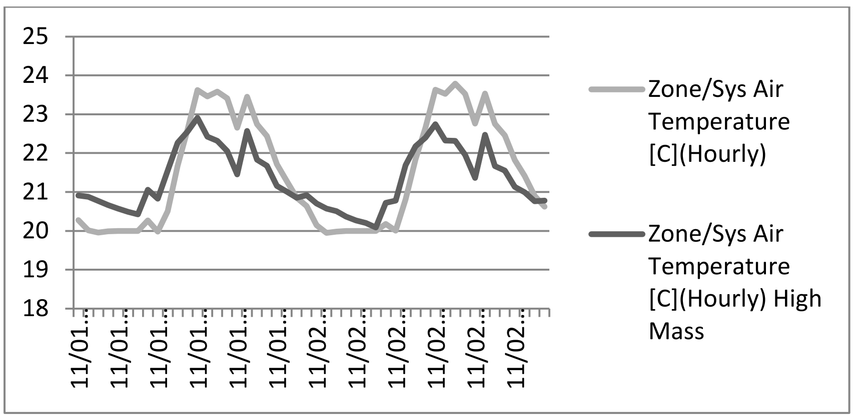

Figure 25 Comparison of indoor air temperature for existing house and high thermal mass incorporation in row house (winter)

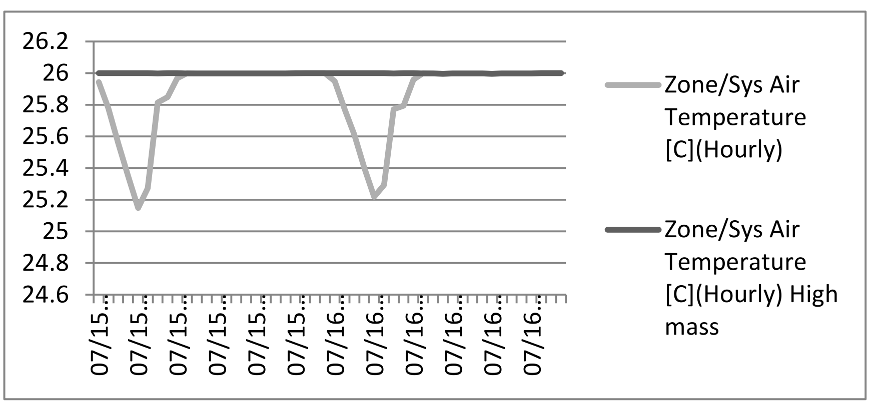

Figure 26 Comparison of indoor air temperature for existing house and high thermal mass incorporation in row house (summer)

5. ANALYSIS OF RESULT AND CONCLUSION

5.1 ANALYSIS OF RESULT

TORONTO	CCHT HOUSE TOTAL ENERGY (GJ)					ROW HOUSE TOTAL ENERGY (GJ)			
	EXISTING	HIGH R	SOUTH GLAZING	REDUCED U VALUE		EXISTING	HIGH R	SOUTH GLAZING	REDUCED U VALUE
EXISTING	50.1	43.5	50.8	47.2		32.6	31.9	33.8	30.8
CEMENT PARTICLE BOARD	48.8	42.13	48.7	46.1		32.2	31.7	34	30.7
CONCRETE WALL INNER LEAF	46.01	39.4	44.6	43.7		31.2	30.6	32.4	29.8
HIGH MASS	45.8	39.3	44.4	43.5		30.7	30	31.8	29.2

Table 29 Total Energy Consumption of CCHT and Row House for Toronto Weather

CCHT twin house has very good strategies (R-2000 Standard, airtightness1.5 ach @50 Pa etc.) as an energy efficient house for which it uses 50.1 GJ/yr. of space conditioning energy for Toronto location, which is less than average Canadian single family dwelling. Also the row house follows OBC 2012 standard for envelope insulation, HVAC requirements, Energy Star airtightness (3 ach@50 pa) etc. for which it consumes total 32.6 GJ/yr. Space conditioning energy. Appendix C provides graphical representations of the heating and cooling energy analysis for CCHT and row house for all the different strategies studied in this research.

Incorporation of thermal mass reduces total energy consumption of the CCHT house up to maximum 4.3 GJ/yr. (8.5% savings) for addition 70760 kg of concrete high mass in the interior surface and for row house it reduces 1.9 GJ/yr.(5.8% savings) for 41440 kg additional concrete in Toronto location.

However with additional insulation CCHT house reduces energy consumption by 6.6 GJ/yr. (13.1% savings). Therefore, it can be said that insulation plays a more significant role in energy reduction rather than thermal mass. However, with increased insulation and thermal mass reduce energy consumption, such as for CCHT house high R value with concrete high mass reduces energy consumption to maximum 39.3 GJ/yr.(Table 29) which is 21.5% maximum savings for an additional weight (70760 kg) of structure.

For the row house triple glazing windows reduce energy consumption up to maximum 1.8 GJ/yr. (5.5% savings) rather than insulation high R value. Because of the size of the structure and its non-heat loss east and west walls. Addition of thermal mass integrated with triple glazing better the energy performance of the row house which reduces maximum 3.4 GJ/yr. (10.4% savings) of total energy with high concrete mass (with additional 41440 kg concrete).

Though increase in south face glazing reduces heating energy consumption in winter, it increases summer cooling energy due to overheating from summer sun. For CCHT house south face glazing increases total energy consumption by 0.7 GJ/yr. and for row house 1.2 GJ/yr. for Toronto location. Integration of thermal mass with this strategy reduces total energy consumption, such as CCHT house reduces maximum 5.7 GJ/yr. of total energy and for row house 0.8 GJ/yr. in Toronto for concrete high mass and increased south face glazing.. Therefore the reduction is better for CCHT house

VANCOUVER	CCHT HOUSE TOTAL ENERGY (GJ)					ROW HOUSE TOTAL ENERGY (GJ)			
	EXISTING	HIGH R	SOUTH GLAZING	REDUCD U VALUE		EXISTING	HIGH R	SOUTH GLAZING	REDUCED U VALUE
EXISTING	32.9	28.7	35.8	30.4		16.5	16.2	18.6	15.2
CEMENT PARTICLE BOARD	31.2	27.2	33	29.1		16.1	15.8	18.4	14.8
CONCRETE WALL INNER LEAF	28.01	24.1	28.2	26.3		15.1	15	17.1	14.2

HIGH MASS	27.7	23.9	27.9	26.03		14.7	14.6	16.6	13.7

Table 30 Total Energy Consumption for CCHT and Row house (Vancouver Weather)

For Vancouver location CCHT house consumes 17.2 GJ (34.3% less) less energy and row house consumes 16.1 GJ (49.3% less) less energy than Toronto because of Vancouver winter temperature is higher and summer temperature in lower than Toronto.

Thermal mass reduces total energy consumption maximum 5.2 GJ/yr. (15.8% savings) for CCHT house and 1.8 GJ/yr. (10.9% savings) for row house with concrete high mass. However, high R walls and ceilings reduce total energy by 4.2 GJ/yr. (12.7% savings) which do not increase weight of CCHT structure to a great extent. Thermal mass integration with insulation high R value reduces energy consumption to a maximum 9 GJ/yr. (27.3% savings) for high concrete mass, which is 4.8 GJ/yr. reduced than insulation high R's energy consumption.

For the row house triple glazing windows reduce energy consumption to 15.2 GJ/yr. (7.8% savings) which is highest reduction among three of the strategies (Table 30). Integration of thermal mass reduces the energy consumption maximum up to 13.7 GJ/yr. (17% savings) for concrete high mass.

Increase in south face glazing increases total energy consumption of both CCHT house (35.8 GJ/yr.) and row house (18.6 GJ/yr.) (8.8% increase for CCHT and 12.7% increase for row house). Thermal mass with increased south face glazing helps in reducing the increment of energy consumption. (27.9 GJ/yr. for CCHT and 16.6 GJ/yr. for row house for concrete high mass.

Thermal mass helps lowering the interior temperatures of the CCHT and row house which maintains comfortable interior with less operation of HVAC system. For high concrete mass interior temperatures do not deviate more or less from set point temperature (20^0-21^0 C for winter and 25^0-26^0 C for summer, though there are heat gains during daytime both in summer and winter times in CCHT and row houses.

5.2 CONCLUSION

Thermal mass plays an important role in reducing energy consumptions; however it increases a large amount of weight to the structure which may have other implications. Also thermal mass can cause significant thermal bridge through its large mass which has higher conductivity than insulation materials. Therefore it can cause significant heat loss through-out the walls, foundation slabs and walls etc. if not carefully detailed. Therefore proper design consideration is required to best use the thermal mass (such as house size, location, location and amount of thermal mass etc.).

Integration of different weight thermal mass reduces energy consumption for both CCHT and row houses. The amount of reduction in CCHT house is greater than row house as row house is smaller in size and it has two non- heat loss walls at east and west side. For the CCHT house concrete high mass increase cooling energy of the house rather than concrete wall in the inner leaf mass whereas for row house concrete high mass reduces maximum energy. Therefore it is suggested that increase in the thermal mass may not always lead to reduced energy use, and, it should be used in adequate amount considering the house requirements.

In CCHT house high R value reduces energy use more than concrete high mass for Toronto. Also a combination of high concrete mass with insulation high R value reduces maximum energy among all the strategies for both Toronto and Vancouver location. Therefore high insulation is better comparing to thermal mass for detached house types in terms energy reduction and thermal mass could be a later choice if it needs more energy reduction considering other factors. (Window area, thermal mass surface area, orientation, climates etc.)

Whereas for the row house, triple glazed windows reduces more energy among three of the strategies. (high R wall, increased south face glazing and reduced window U value).However this reduction is lower than concrete high mass’s reduction. Also a combination of concrete high mass with triple glazed window reduces maximum energy among all the strategies for both Toronto and Vancouver location.

South face glazing can be a good strategy for energy reduction if it can be used with thermal mass to reduce summer overheating. Because increase in the south face glazing on its own increases energy consumption for both CCHT and row houses whereas addition of thermal mass reduces the amount of increment in energy consumption.

Percent energy savings with thermal mass is greater for Vancouver location for both CCHT and row house, which indicates that thermal mass shows better performance in warmer location rather than colder ones.

Moreover thermal mass slows indoor air temperature fluctuations more than the light weight structure. For high concrete mass both CCHT and row house reduces indoor temperature fluctuations from setpoint temperature (winter and summer) which plays a significant role to keep the house comfortable and reduced HVAC operation.

6 FUTURE WORK

The future research potential on thermal mass performance can be done with the integration of natural ventilation in the houses to see how these two combinations can reduce energy consumption of the houses as well as increase occupant thermal comfort. To assess natural ventilation, it is required to set up an airflow network to account infiltration rate of outside air and stack effect of the building. Also with natural ventilation, application of shading devices can be included as a means of reduced overheating. Also the potential of different thermal mass materials with their best placement in the houses can be investigated for further study.

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8. APPENDICES

8.1 APPENDIX A – PARAMETERS USED IN ENERGY PLUS MODELING FOR CCHT AND ROW HOUSE

CCHT AND ROW HOUSE MATERIAL PROPERTIES

Material	Roughness	Thickness {m}	Conductivity {W/m-K}	Density {kg/m3}	Specific Heat {J/kg-K}	Thermal Absorptance	Solar Absorptance	Visible Absorptance
Concrete 75	Rough	0.075	1.13	2000	1000	0.9	0.6	0.6
Concrete 200	Rough	0.2	1.13	2000	1000	0.9	0.6	0.6
Tile	Rough	0.0127	1.13	2000	1000	0.9	0.6	0.6
XPS	Rough	0.1	0.034	35	1400	0.9	0.6	0.6
Brick	Rough	0.1	0.72	1920	800	0.9	0.6	0.6
Gypsum	Rough	0.0127	0.16	640	1150	0.9	0.2	0.6
OSB	Rough	0.016	0.091	650	1880	0.9	0.4	0.6
Insulation AG	Rough	0.14	0.0493	14	840	0.9		
Insulation AGw	Rough	0.14	0.0529	14	840	0.9		
Insulation AG (row)	Rough	0.25	0.0493	14	840	0.9		
Insulation AGw (row)	Rough	0.10	0.0529	14	840	0.9		
Insulation BG	Rough	0.089	0.0489	14	840	0.9		
Ceiling Insulation	Rough	0.3658	0.0453	14	840	0.9		
GarageCeilingInsulation	Rough	0.292	0.0448	14	840	0.9		
Insulation BG (row)	Rough	0.15	0.0489	14	840	0.9		
Ceiling Insulation (row)	Rough	0.45	0.0453	14	840	0.9		
GarageCeilingInsulation (row)	Rough	0.35	0.0448	14	840	0.9		
Shingles_Asphalt	Rough	0.003	0.038	920	1510	0.9	0.9	0.9
Concrete 30	Rough	0.3	1.13		2000	1000	0.9	0.6
Gypsum_w	Rough	0.001	0.16	640	1150	0.9	0.2	0.6

MATERIAL: AIR GAP

Name	Thermal Resistance {m2-K/W}
AirSpace20	0.16
AirSpace90horiz	0.16
AirSpace90vertical	0.15

CCHT WINDOW MATERIAL: GLAZING

Name	layer1	layer2
Optical Data Type	Spectral Average	Spectral Average
Window Glass Spectral Data Set Name		
Thickness {m}	0.003	0.003023
Solar Transmittance at Normal Incidence	0.837	0.692
Front Side Solar Reflectance at Normal Incidence	0.075	0.122
Back Side Solar Reflectance at Normal Incidence	0.075	0.112
Visible Transmittance at Normal Incidence	0.899	0.824
Front Side Visible Reflectance at Normal Incidence	0.083	0.115
Back Side Visible Reflectance at Normal Incidence	0.083	0.110
Infrared Transmittance at Normal Incidence	0	0
Front Side Infrared Hemispherical Emissivity	0.84	0.156
Back Side Infrared Hemispherical Emissivity	0.84	0.840
Conductivity {W/m-K}	1	1
Solar Diffusing	No	No

ROW HOUSE WINDOW MATERIAL: GLAZING

Name	layer1	layer2
Optical Data Type	Spectral Average	Spectral Average
Window Glass Spectral Data Set Name		

Thickness {m}	0.003	0.003
Solar Transmittance at Normal Incidence	0.3933	0.4818
Front Side Solar Reflectance at Normal Incidence	0.075	0.122
Back Side Solar Reflectance at Normal Incidence	0.075	0.112
Visible Transmittance at Normal Incidence	0.72	0.72
Front Side Visible Reflectance at Normal Incidence	0.083	0.115
Back Side Visible Reflectance at Normal Incidence	0.083	0.110
Infrared Transmittance at Normal Incidence	0	0
Front Side Infrared Hemispherical Emissivity	0.84	0.156
Back Side Infrared Hemispherical Emissivity	0.84	0.840
Conductivity {W/m-K}	0.08	0.1
Solar Diffusing	No	No

WINDOW MATERIAL: GAS MIXTURE

Name	gap1
Thickness {m}	0.0125
Number of Gases in Mixture	2
Gas 1 Type	Argon
Gas 1 Fraction	0.95
Gas 2 Type	Air
Gas 2 Fraction	0.05

CCHT AND ROW HOUSE CONSTRUCTION DETAILS

Name	Outside Layer	Layer 2	Layer 3	Layer 4	
Brick_ Wall	Brick	OSB	Insulation AG	Gypsum	
Brick_ Wall_ w	Brick	OSB	Insulation AGw	Gypsum	
Basement_ floor	concrete 75				
ceiling_ insulated	Ceiling Insulation	Gypsum			
ceiling_ insulated_ reverse	Gypsum	Ceiling Insulation			
Roof_ uninsulated	Shingles_Asphalt	OSB			
Roof_ insulated	Shingles_Asphalt	OSB	Ceiling Insulation	Gypsum	
Brick_Wall_Uninsulated	Brick	OSB	airspace20	OSB	
below_grade	Concrete 200	airspace20	Insulation BG	Gypsum	
garage_ceiling	GarageCeilingInsulation				
interior_garage_wall	Gypsum	Insulation AG	Gypsum		
interior_floor	Gypsum	AirSpace90horiz	OSB		
interior_floor_rev	OSB	AirSpace90horiz	Gypsum		
interior_floor_tile	Gypsum	AirSpace90horiz	OSB	Tile	

interior_floor_tile_rev	Tile	OSB	AirSpace90horiz	Gypsum	
interior walls	Gypsum	AirSpace90vertical	Gypsum		
porch floor	Concrete 30				
door_insulated	door_material_insulated				
CCHT and row Ref Windows Hshg	layer1	gap1	layer2		
wall_w	Gypsum_w	Insulation AGw	AirSpace90vertica	Insulation AGw	Gypsum_w

CCHT AND ROW HOUSE WINDOW PROPERTY: FRAME AND DIVIDER

Name	CCHT Ref Frames
Frame Width {m}	0.1
Frame Outside Projection {m}	0.01
Frame Inside Projection {m}	0.025
Frame Conductance {W/m^2-K}	1.89
Ratio of Frame-Edge Glass Conductance to Center-Of-Glass Conductance	1.07
Frame Solar Absorptance	0.15
Frame Visible Absorptance	0.2
Frame Thermal Hemispherical Emissivity	0.9

CCHT AND ROW HOUSE INTERNALMASS

Name	Construction Name	Zone Name	Surface Area {m^2}
Upstairs Floor	interior_floor	Zone 1	170.6
Main ceiling	interior_floor_rev	Zone 1	143.2
Zone 1 partitions	interior walls	Zone 1	270

PEOPLE/OCCUPANTS

Name	Occupants
Zone or Zone List Name	Zone 1
Number of People Schedule Name	Occupancy Schedule
Number of People Calculation Method	People
Number of People	4
People per Zone Floor Area {person/m2}	
Zone Floor Area per Person {m2/person}	
Fraction Radiant	0.5,
Sensible Heat Fraction	
Activity Level Schedule Name	Occupant Activity Schedule

CCHT AND ROW HOUSE LIGHTS

Name	CCHT 2nd floor lights	CCHT Main floor lights	Row house 2nd floor lights	Row house 3rd floor lights

Zone or Zone List Name	Zone 1	Zone 1	Zone 1	Zone 1
Schedule Name	2nd Floor Light Schedule	Main Floor Light Schedule	2nd Floor Light Schedule	3rd Floor Light Schedule
Design Level Calculation Method	Lighting Level	Lighting Level	Lighting Level	Lighting Level
Lighting Level {W}	410	200	9.6 w/m^2	6.5w/m^2
Return Air Fraction	0	0	0	0
Fraction Radiant	0.95	0.95	0.95	0.95
Fraction Visible	0.05	0.05	0.05	0.05
Fraction Replaceable	1	1	1	1
End-Use Subcategory	Zone1 Lights	Zone1 Lights	Zone1 Lights	Zone1 Lights
Return Air Fraction Calculated from Plenum Temperature	No	No	No	No

HOT WATER EQUIPMENT

Name	Zone1DHW
Zone or Zone List Name	All Living Space Zones
Schedule Name	Always On Schedule
Design Level Calculation Method	Equipment Level
Design Level {W}	250
Fraction Latent	0.2
Fraction Radiant	0.1
Fraction Lost	0.6
End Use Subcategory	Zone1 DHW

CCHT ZONE INFILTRATION: DESIGN FLOW RATE

Name	attic_ach	Garage_ach
Zone or Zone List Name	attic_zone	Garage_Zone
Schedule Name	Inf_schedule	Inf_schedule
Design Flow Rate Calculation Method	AirChanges/Hour	AirChanges/Hour
Air Changes per Hour	0.75	0.15
Constant Term Coefficient	0	0
Temperature Term Coefficient	0	0
Velocity Term Coefficient	0.224	0.244
Velocity Squared Term Coefficient	0	0

ROW HOUSE ZONE INFILTRATION: DESIGN FLOW RATE

Name	attic_ach	Garage_ach
Zone or Zone List Name	attic_zone	Garage_Zone
Schedule Name	Inf_schedule	Inf_schedule
Design Flow Rate Calculation Method	AirChanges/Hour	AirChanges/Hour
Air Changes per Hour	1.5	0.30
Constant Term Coefficient	0	0
Temperature Term Coefficient	0	0

Velocity Term Coefficient	0.224	0.244
Velocity Squared Term Coefficient	0	0

CCHT AND ROW HOUSE ZONE INFILTRATION: FLOW COEFFICIENT

Name	zone_inf_coeffs zone 1	zone_inf_coeffs bsmt
Zone Name	Zone 1	Basement_zone
Schedule Name	always on schedule	always on schedule
Flow Coefficient	0.02296	0.02296
Stack Coefficient	0.078	0.078
Pressure Exponent	0.699	0.699
Wind Coefficient	0.17	0.17
Shelter Factor	0.7	0.15

CCHT AND ROW HOUSE: SIZING: HVAC SYSTEM

Air Loop Name	Air Loop HVAC
Type of Load to Size On	Sensible
Design Outdoor Air Flow Rate {m3/s}	Auto size
Minimum System Air Flow Ratio	1
Preheat Design Temperature {C}	7
Preheat Design Humidity Ratio {kgH2O/kg Air}	0.008
Precool Design Temperature {C}	12.8
Precool Design Humidity Ratio {kg H_2O/kg Air}	0.008
Central Cooling Design Supply Air Temperature {C}	12.8
Central Heating Design Supply Air Temperature {C}	40
Sizing Option	Non Coincident
100% Outdoor Air in Cooling	No
100% Outdoor Air in Heating	No
Central Cooling Design Supply Air Humidity Ratio {kg	0.008
Central Heating Design Supply Air Humidity Ratio {kg	0.008
Cooling Design Air Flow Method	Design Day
Cooling Design Air Flow Rate {m3/s}	Design Day

CCHT AND ROW HOUSE: ZONE HVAC: ENERGY RECOVERY VENTILATOR

Name	Venmar HRV
Availability Schedule Name	HRV_Schedule
Heat Exchanger Name	HRV Heat Exchanger
Supply Air Flow Rate {m3/s}	0.03
Exhaust Air Flow Rate {m3/s}	0.03
Supply Air Fan Name	HRV Supply Fan
Exhaust Air Fan Name	HRV Exhaust Fan

CCHT AND ROW HOUSE: Fan: On Off

Name	Air loop HVAC Fan	HRV Supply Fan	HRV Exhaust Fan
Availability Schedule Name	Zone1 Dual Zone Control	HRV_Schedule	HRV_Schedule
Fan Efficiency	1	0.7	0.7
Pressure Rise {Pa}	124	125	125
Maximum Flow Rate {m3/s}	0.68	0.04	0.04
Motor Efficiency	1	0.9	0.9
Motor In Airstream Fraction	0	1	1
Air Inlet Node Name	Node3a	HRV_Supply_Air_Node	HRV_Exhaust_Air_Nod e
Air Outlet Node Name	node9	HRV_Zone_Supply_Node	OA_Exhaust_Node
End-Use Subcategory	General	HRV	HRV

CCHT AND ROW HOUSE :COIL: COOLING: DX: SINGLE SPEED

Name	Furnace_ Coil
Availability Schedule Name	Zone1coolingSetPoint
Rated Total Cooling Capacity {W}	18000
Rated Sensible Heat Ratio	0.6
Rated COP {W/W}	3
Rated Air Flow Rate {m3/s}	0.68
Rated Evaporator Fan Power Per Volume Flow Rate {W/(m3/s)}	773.3
Air Inlet Node Name	node9
Air Outlet Node Name	node10a
Condenser Type	Air Cooled

COIL: HEATING: GAS

Name	CCHT Furnace Coil	Row house Furnace coil
Availability Schedule Name	Zone1HeatingSetpoint	Zone1HeatingSetpoint
Gas Burner Efficiency	0.802	0.84
Nominal Capacity {W}	19778	19000
Air Inlet Node Name	node10a	node10a
Air Outlet Node Name	node10b	node10b
Parasitic Electric Load {W}	10	10
Parasitic Gas Load {W}	0	0

HEAT EXCHANGER: AIR TO AIR: SENSIBLE AND LATENT

Name	CCHT HRV Heat Exchanger	Row House HRV Heat Exchanger
Availability Schedule Name	HRV_Schedule	HRV_Schedule
Nominal Supply Air Flow Rate {m3/s}	0.03	0.03
Sensible Effectiveness at 100% Heating Air Flow {dimensionless}	0.84	0.55
Latent Effectiveness at 100% Heating Air Flow {dimensionless}	0	0
Sensible Effectiveness at 75% Heating Air Flow {dimensionless}	0.84	0.55
Latent Effectiveness at 75% Heating Air Flow {dimensionless}	0	0
Heat Exchanger Type	Plate	Plate
Frost Control Type	Exhaust Air Recirculation	Exhaust Air Recirculation
Threshold Temperature {C}	-5	-5
Initial Defrost Time Fraction {dimensionless}	0.1	0.1
Rate of Defrost Time Fraction Increase {1/K}	0.0091	0.0091

CCHT AND ROW HOUSE: AIR LOOP HVAC: UNITARY: HEAT COOL

Name	A2HVAC
Availability Schedule Name	Zone1Control
Furnace Air Inlet Node Name	Node3a
Furnace Air Outlet Node Name	node10b
Supply Air Fan Operating Mode Schedule Name	Furnace Fan Operating Mode Schedule,
Maximum Supply Air Temperature {C}	80
Supply Air Flow Rate During Cooling Operation {m3/s}	0.622
Supply Air Flow Rate During Heating Operation {m3/s}	0.622
Supply Air Flow Rate When No Cooling or Heating is Needed {m3/s}	0.45
Controlling Zone or Thermostat Location	Zone 1
Supply Fan Object Type	Fan:OnOff
Supply Fan Name	CCHT Furnace Fan
Fan Placement	Blow Through
Heating Coil Object Type	Coil: Heating: Gas
Heating Coil Name	Furnace Coil
Cooling Coil Object Type	Coil: Cooling: DX: Single Speed
Cooling Coil Name	Furnace_ Coil
Dehumidification Control Type	None
System Outdoor Air Method	Ventilation Rate Procedure

CEMENT PARTICLE BOARD MASS FOR CCHT AND ROW HOUSE:

Material Properties: Cement Particle Board

Name	Cement particle board
Roughness	Rough
Thickness {m}	0.012
Conductivity {W/m K}	0.26
Density {kg/m3}	1250
Specific Heat {J/kg K}	1300
Thermal Absorptance	0.9
Solar Absorptance	0.6
Visible Absorptance	0.6

CCHT AND ROW HOUSE CONSTRUCTION

Name	Outside Layer	Layer 2	Layer 3	Layer 4	Layer 5
Brick_Wall	Brick	OSB	Insulation AG	cementparticle board	
Brick_Wall_w	Brick	OSB	Insulation AGw	cementparticle board	
interior_garage_wall	Gypsum	Insulation AG	cementparticle board		
interior_floor	Gypsum	AirSpace90horiz	OSB	cementparticle board	
interior_floor_rev	cementparticle board	OSB	AirSpace90horiz	Gypsum	
interior_floor_tile	Gypsum	AirSpace90horiz	OSB	cementparticle board	Tile
interior_floor_tile_rev	Tile	cementparticle board	OSB	AirSpace90horiz	Gypsum
interior walls	cementparticle board	Gypsum			
wall_w	cementparticle board_w	Insulation AGw (row)	AirSpace90vertica	Insulation AGw (row)	cementparticle board_w

CONCRETE WALL MASS:

Name	Outside Layer	Layer 2	Layer 3	Layer 4	Layer 5
Brick_Wall	Brick	OSB	Insulation AG	Concrete 100	
Brick_Wall_w	Brick	OSB	Insulation AGw	Concrete 100	

Brick_Wall (row)	Brick	OSB	Insulation AG (row)	Concrete 100	
Brick_Wall_w (row)	Brick	OSB	Insulation AGw (row)	Concrete 100	
interior_garage_wall	Gypsum	Insulation AG	Concrete 100		
interior walls	Concrete 100	AirSpace90vertical	Concrete 100		
wall_w	Concrete 100	Insulation AGw (row)	AirSpace90vertica	Insulation AGw (row)	Concrete 100

CONCRETE HIGH MASS:

Name	Outside Layer	Layer 2	Layer 3	Layer 4	Layer 5
Brick_Wall	Brick	OSB	Insulation AG	Concrete 100	
Brick_Wall_w	Brick	OSB	Insulation AGw	Concrete 100	
interior_garage_wall	Gypsum	Insulation AG	Concrete 100		
interior_floor	Gypsum	AirSpace90horiz	OSB	Concrete 100	
interior_floor_rev	Concrete 100	OSB	AirSpace90horiz	Gypsum	
interior_floor_tile	Gypsum	AirSpace90horiz	OSB	Concrete 100	Tile
interior_floor_tile_rev	Tile	Concrete 100	OSB	AirSpace90horiz	Gypsum
interior walls	Concrete 100	Gypsum			

CCHT HIGH R VALUE FOR INSULATION:

Name	Insulation AG	Insulation AGw	Insulation BG	Ceiling Insulation	Garage Ceiling Insulation
Roughness	Rough	Rough	Rough	Rough	Rough
Thickness {m}	0.20	0.20	0.1	0.45	0.35
Conductivity {W/m K}	0.0493	0.0529	0.0489	0.0453	0.0448
Density {kg/m3}	14	14	14	14	14
Specific Heat {J/kg K}	840	840	840	840	840
Thermal Absorptance	0.9	0.9	0.9	0.9	0.9

CCHT GLAZING U VALUE CHANGE

Name	LAYER 1	LAYER 2	LAYER 3
Optical Data Type	Spectral Average	Spectral Average	Spectral Average
Window Glass Spectral Data Set Name			
Thickness {m}	0.003	0.003023	0.003
Solar Transmittance at Normal Incidence	0.837	0.692	0.837
Front Side Solar Reflectance at Normal Incidence	0.075	0.122	0.075
Back Side Solar Reflectance at Normal Incidence	0.075	0.112	0.075
Visible Transmittance at Normal Incidence	0.899	0.824	0.899
Front Side Visible Reflectance at Normal Incidence	0.083	0.115	0.083
Back Side Visible Reflectance at Normal Incidence	0.083	0.110	0.083
Infrared Transmittance at Normal Incidence	0	0	0
Front Side Infrared Hemispherical Emissivity	0.84	0.156	0.84
Back Side Infrared Hemispherical Emissivity	0.84	0.840	0.84
Conductivity {W/m-K}	1	1	1

ROW HOUSE U VALUE CHANGE

Name	LAYER 1	LAYER 2	LAYER 3
Optical Data Type	Spectral Average	Spectral Average	Spectral Average
Window Glass Spectral Data Set Name			
Thickness {m}	0.003	0.003	0.003
Solar Transmittance at Normal Incidence	0.3933	0.4818	0.3933
Front Side Solar Reflectance at Normal Incidence	0.075	0.122	0.075
Back Side Solar Reflectance at Normal Incidence	0.075	0.112	0.075
Visible Transmittance at Normal Incidence	0.72	0.72	0.72
Front Side Visible Reflectance at Normal Incidence	0.083	0.115	0.083
Back Side Visible Reflectance at Normal Incidence	0.083	0.110	0.083
Infrared Transmittance at Normal Incidence	0	0	0
Front Side Infrared Hemispherical Emissivity	0.84	0.156	0.84
Back Side Infrared Hemispherical Emissivity	0.84	0.840	0.84

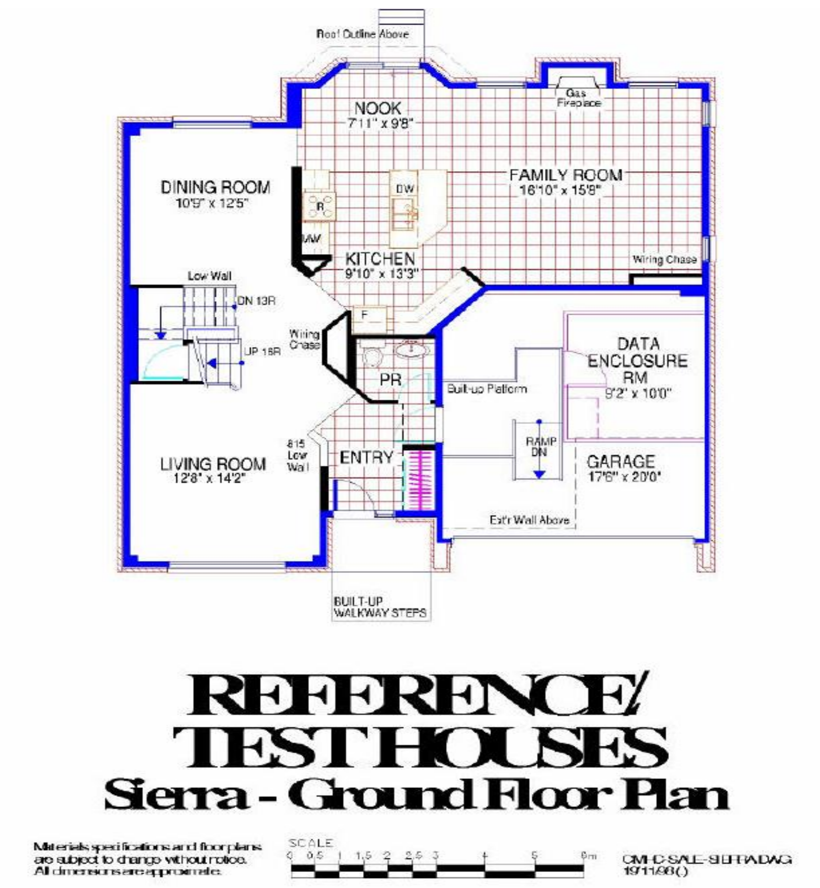
Conductivity {W/m-K}	0.08	0.1	0.08

WINDOW MATERIAL: GAS MIXTURE

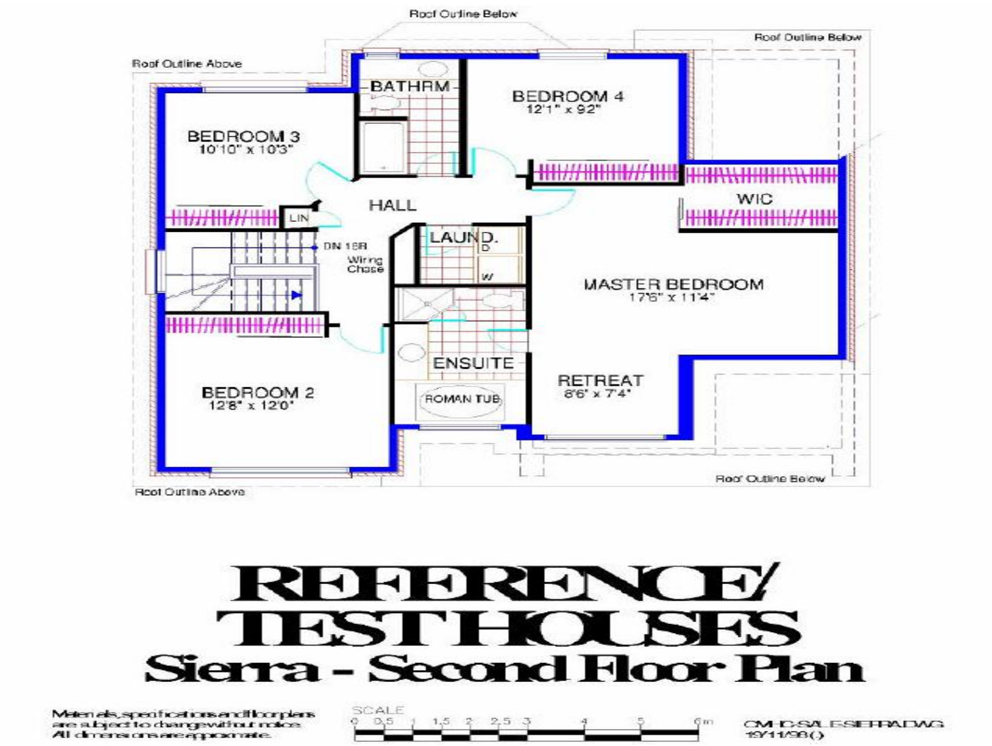
Name	gap1	gap 2
Thickness {m}	0.0125	0.0125
Number of Gases in Mixture	2	2
Gas 1 Type	Argon	Argon
Gas 1 Fraction	0.95	0.95
Gas 2 Type	Air	Air
Gas 2 Fraction	0.05	0.05

8.2 APPENDIX B- FLOOR PLANS FOR CCHT AND ROW HOUSE

CCHT HOUSE GROUND FLOOR PLAN:



CCHT HOUSE SECOND FLOOR PLAN



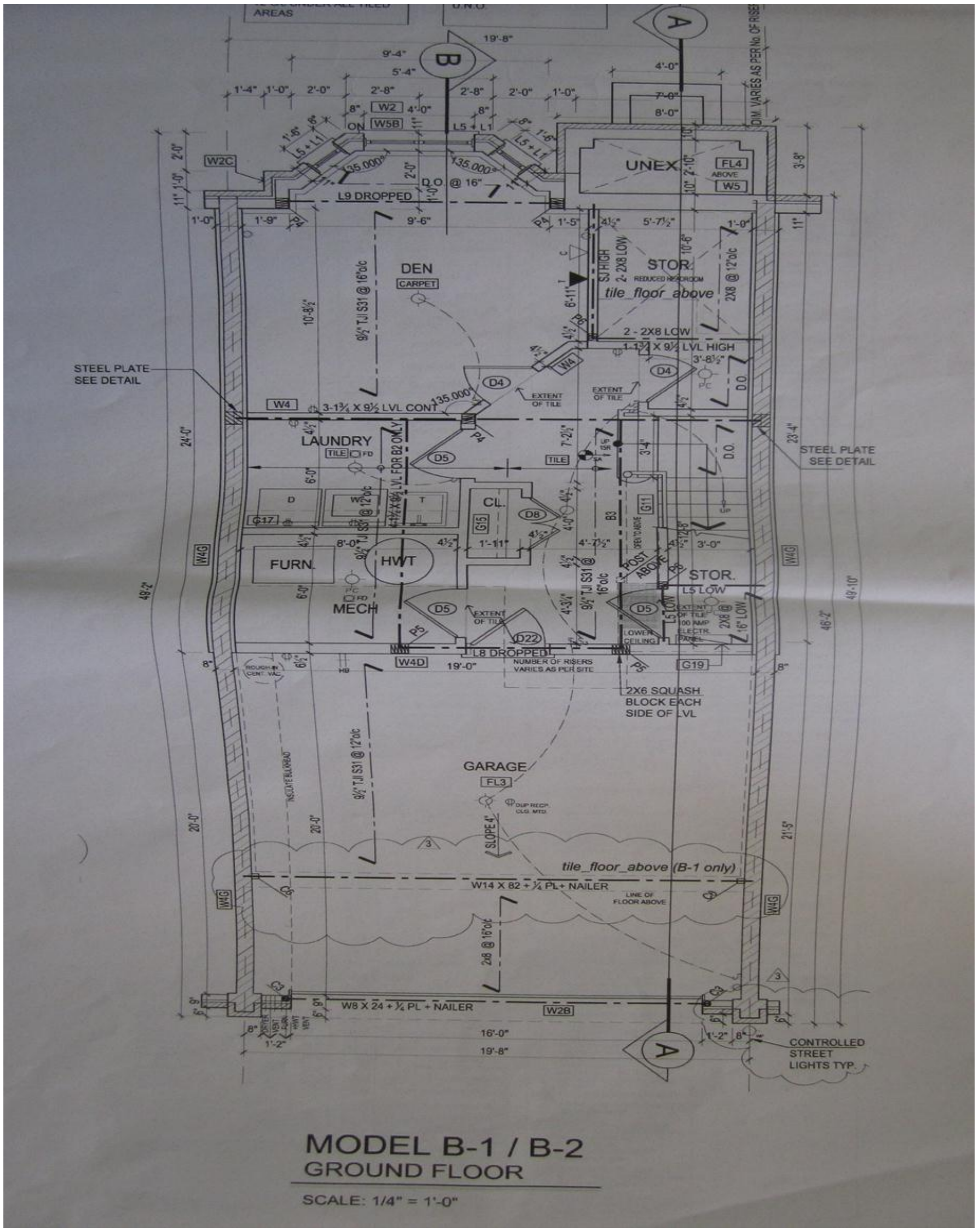
CCHT HOUSE OUTSIDE VIEW:

CCHT Simulated Occupancy Schedule - Sept 13th, 2002

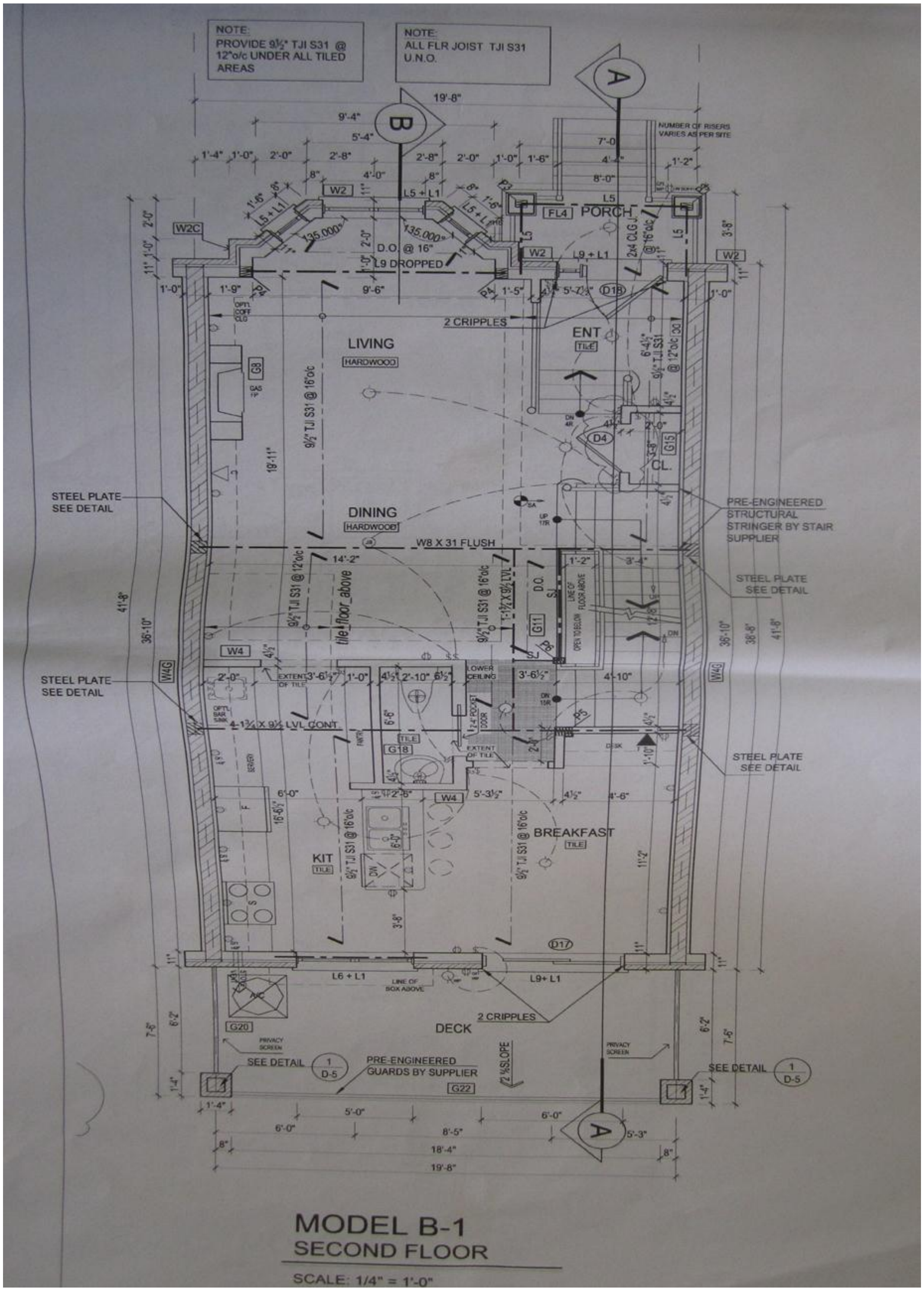
Note: Water draws shown here are for hot water only, in liters.

Device	Water Utility	Draw	Time	Duration
Overnight				
Device	Water Utility	Draw	Time	Duration
Bedroom 2 humans		66.4 W	0:00	6 hrs 45 min
Master bedroom humans		99.6 W	0:00	6 hrs 45 min
Morning				
Device	Water Utility	Draw	Time	Duration
2nd floor lights		410 W	6:45	60.0 min
	1. Master bedroom shower	36 L	6:50	10.2 min
Family room humans		166 W	7:00	60.0 min
Main floor lights		200 W	7:00	60.0 min
Kitchen products		450 W	7:30	10.2 min
Kitchen fan		80 W	7:30	10.2 min
Kitchen stove (intermittent)		1600 W	7:30	20.0 min
	2. Kitchen tap	13 L	7:45	3.0 min
Afternoon				
Device	Water Utility	Draw	Time	Duration
Kitchen fan		80 W	12:00	15.0 min
Kitchen stove (intermittent)		1600 W	12:00	15.0 min
Family room humans		166 W	12:00	30.0 min
Kitchen products		450 W	12:00	10.2 min
Main floor lights		200 W	12:00	15.0 min
	3. Kitchen tap	13 L	12:30	3.0 min
Evening				
Device	Water Utility	Draw	Time	Duration
	4 & 5. Clothes washer (46L)	400 W	17:00	60.0 min
Main floor lights		200 W	17:00	2 hrs 30 min
Kitchen fan		80 W	17:30	3.6 min
Kitchen stove (intermittent)		1600 W	17:30	30.0 min
Family room humans		166 W	17:30	2 hrs 30 min
Kitchen products		450 W	17:30	10.2 min
Dining room products		225 W	18:00	2 hrs
2nd floor lights		410 W	18:00	5 hrs
	6. Kitchen tap	27 L	18:30	6.0 min
	7 & 8. Dishwasher	650 W	19:00	60.0 min
Dryer		2250 W	19:00	25.2 min
Living room humans		166 W	19:00	2 hrs
Bedroom 2 humans		66 W	21:00	3 hrs
	9. Main bathroom bath	41 L	21:05	4.8 min
	10. Master bedroom shower	55 L	22:30	15 min
Master Bedroom Humans		100 W	23:00	60 min

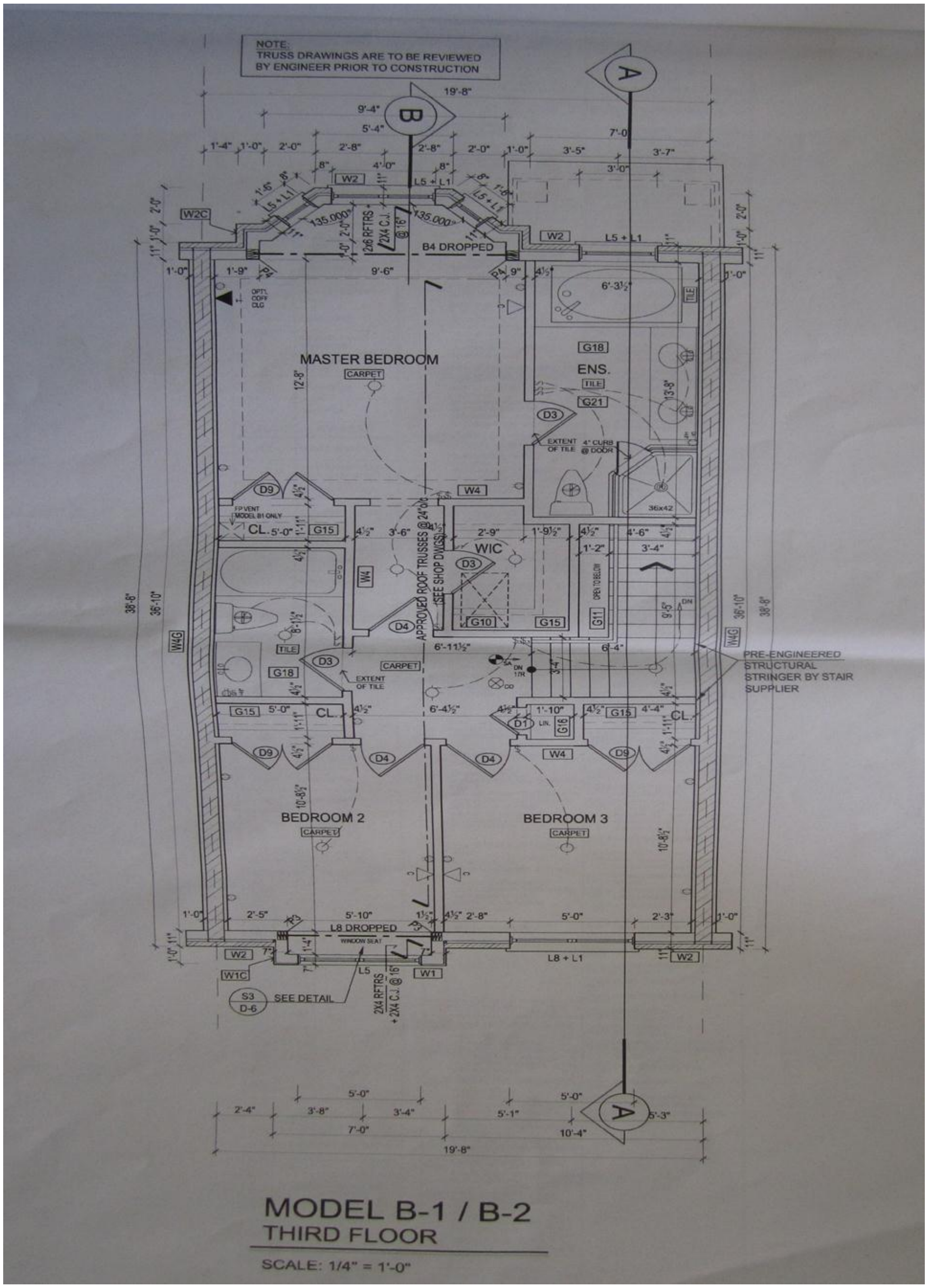
ROW HOUSE GROUND FLOOR PLAN



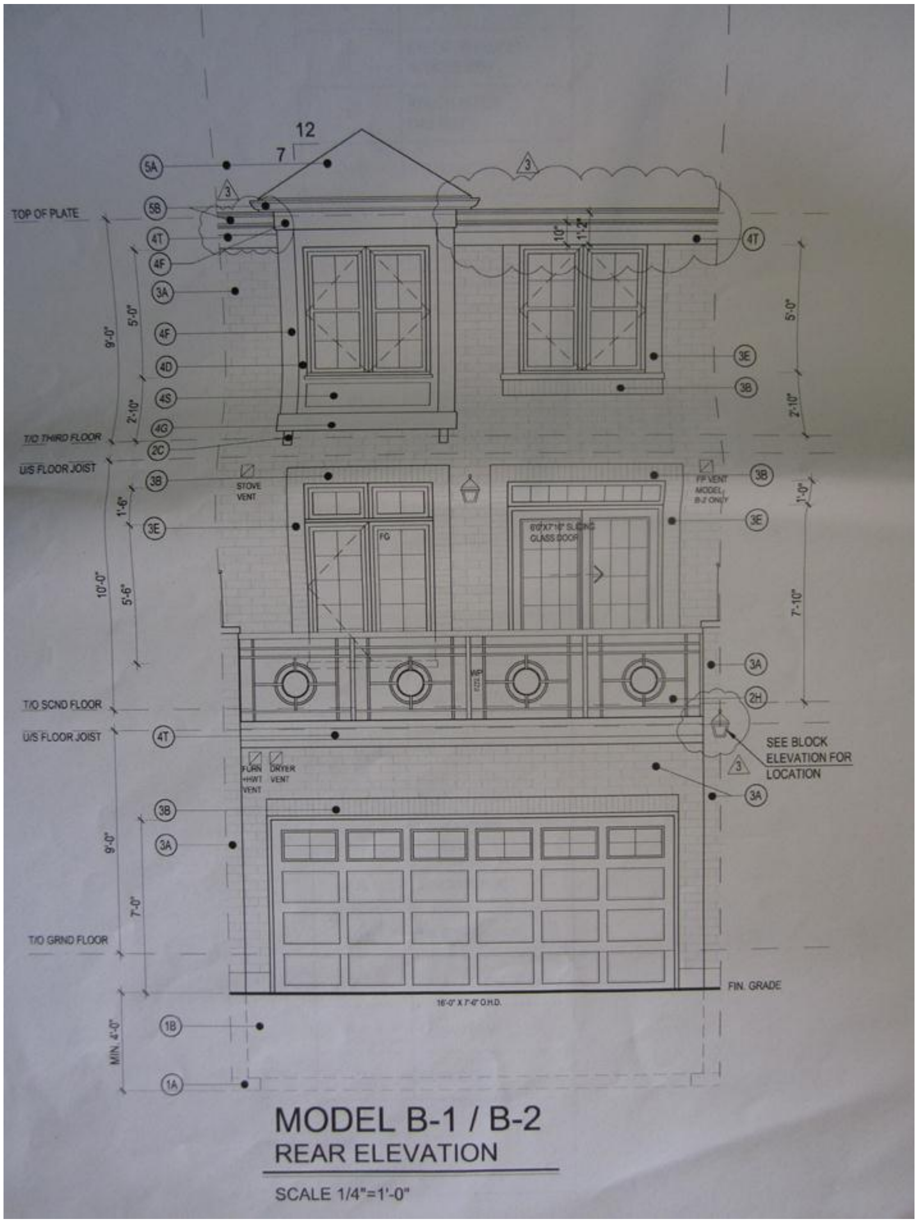
ROW HOUSE SECOND FLOOR PLAN



ROW HOUSE THIRD FLOOR PLAN

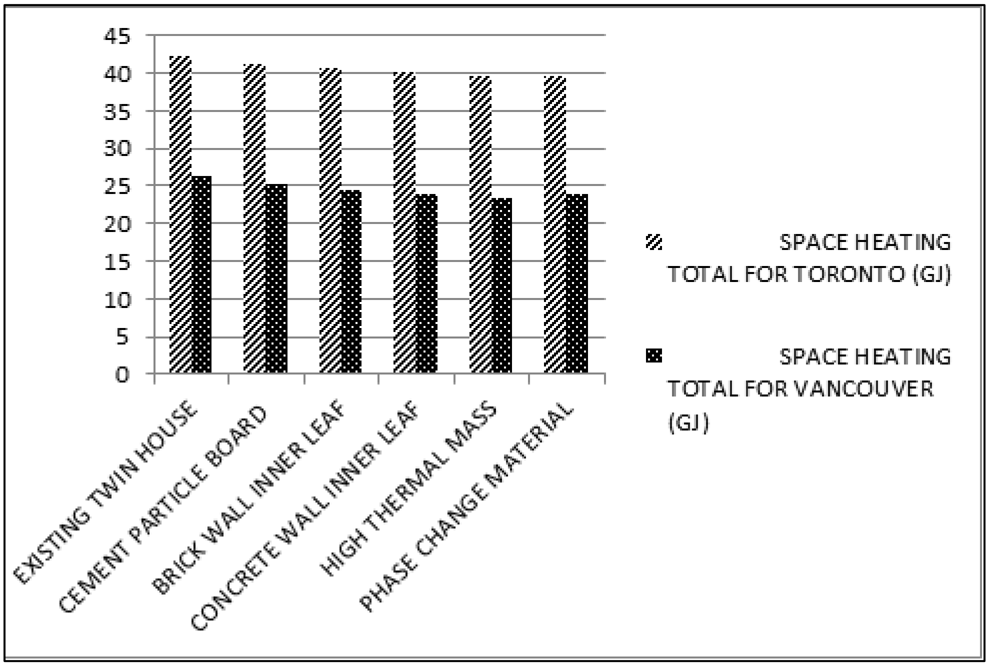


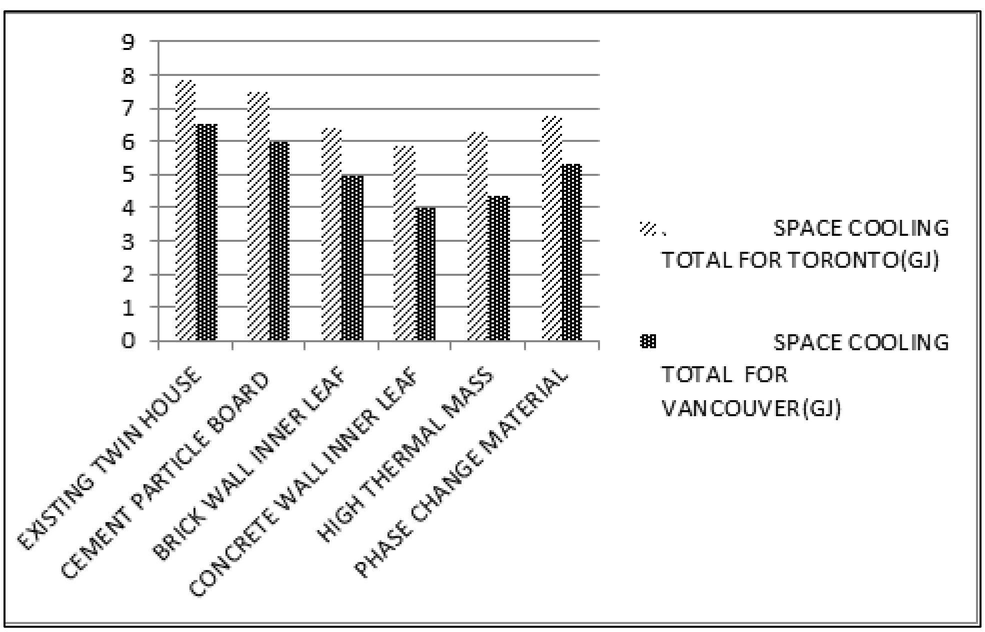
ROW HOUSE REAR VIEW ELEVATION



8.3 APPENDIX C- HEATING AND COOLING ENERGY GRAPHS FOR CCHT AND ROW HOUSE

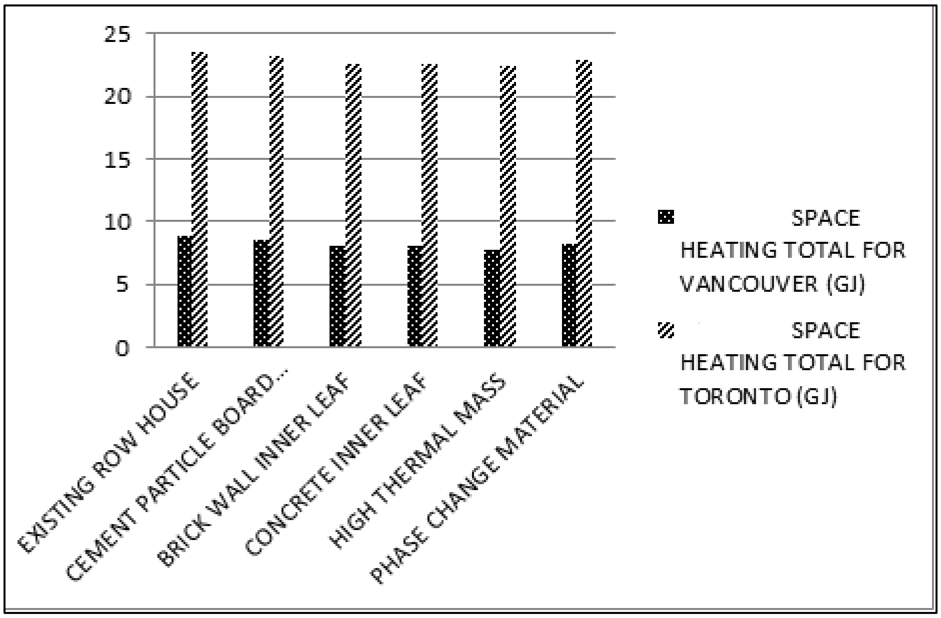
CCHT HEATING AND COOLING ENERGY GRAPHS – Different Thermal Mass

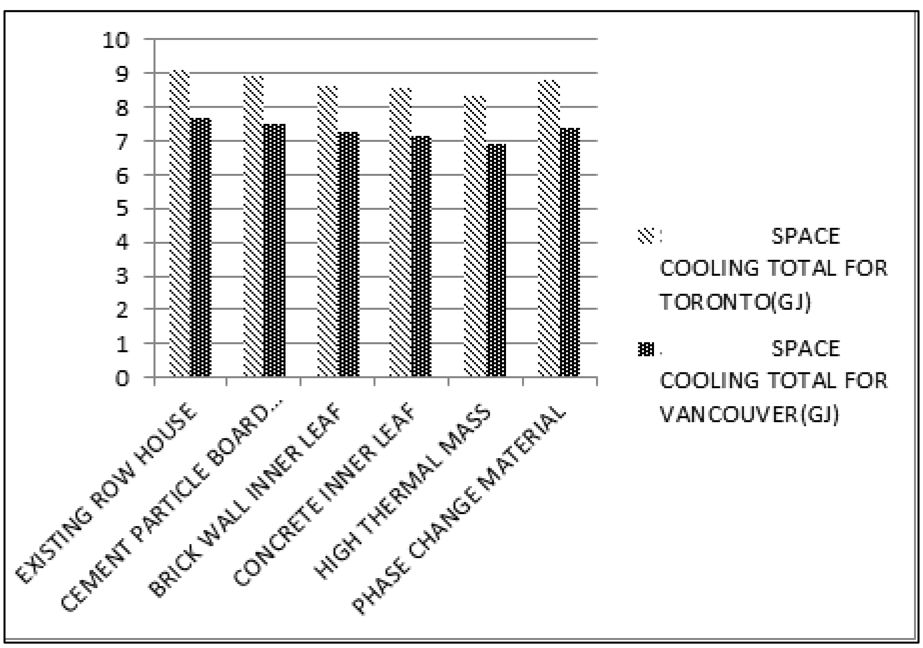




ROW HOUSE HEATING AND COOLING ENERGY GRAPHS –

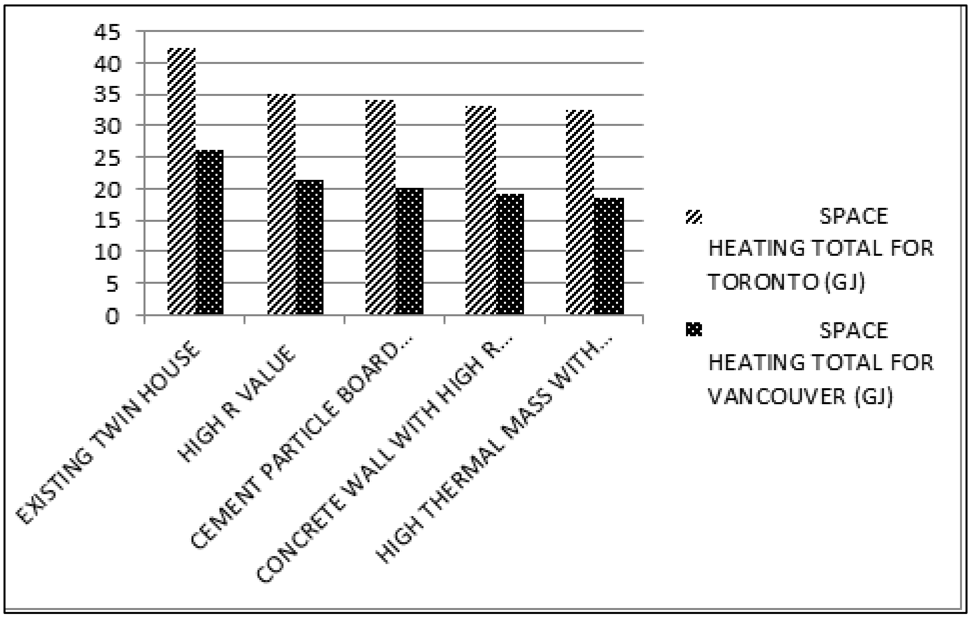
Different Thermal Mass

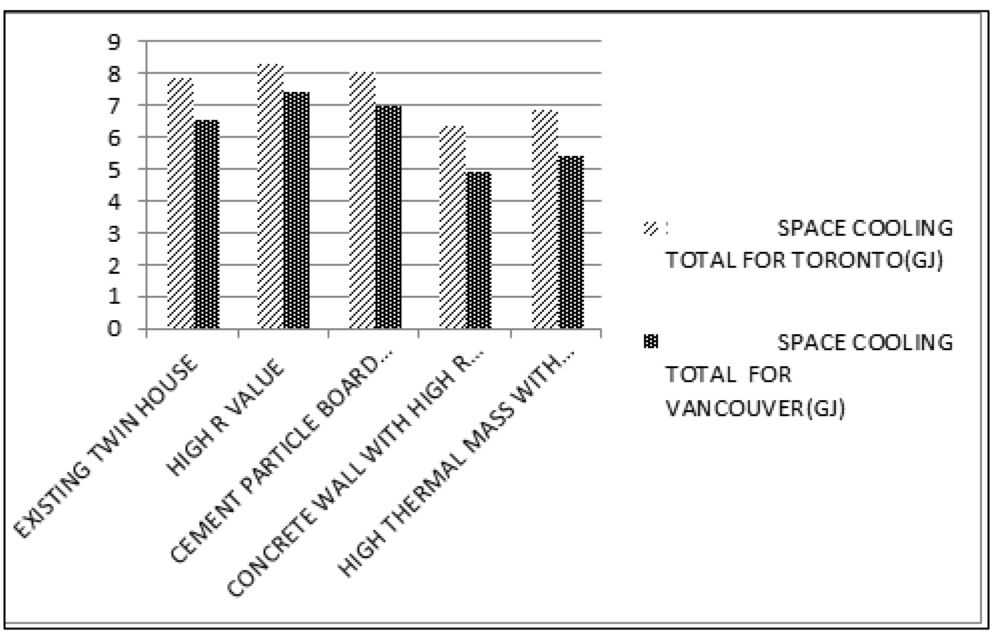




CCHT HEATING AND COOLING ENERGY ANALYSIS –

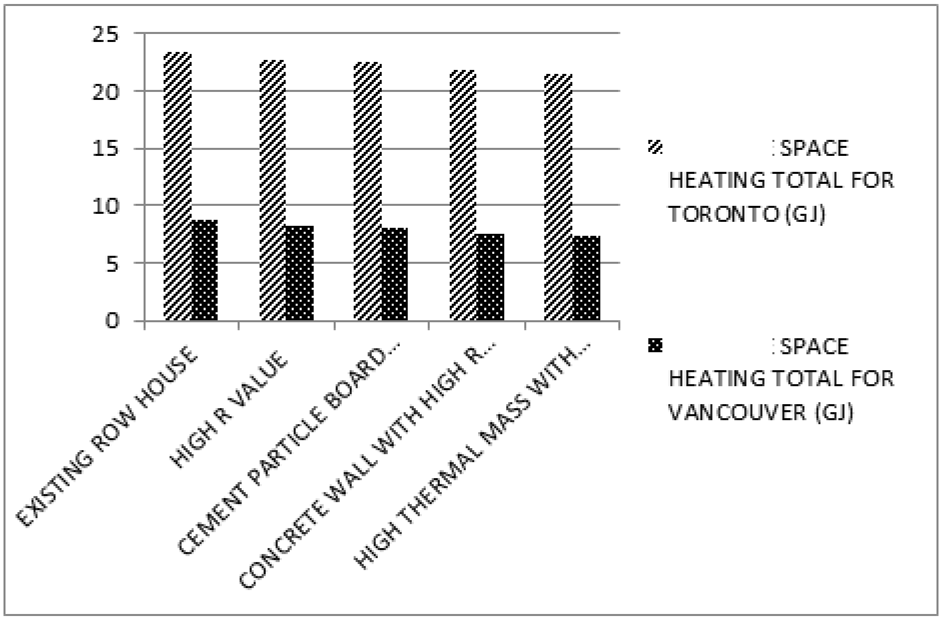
Insulation increased R value and Thermal Mass

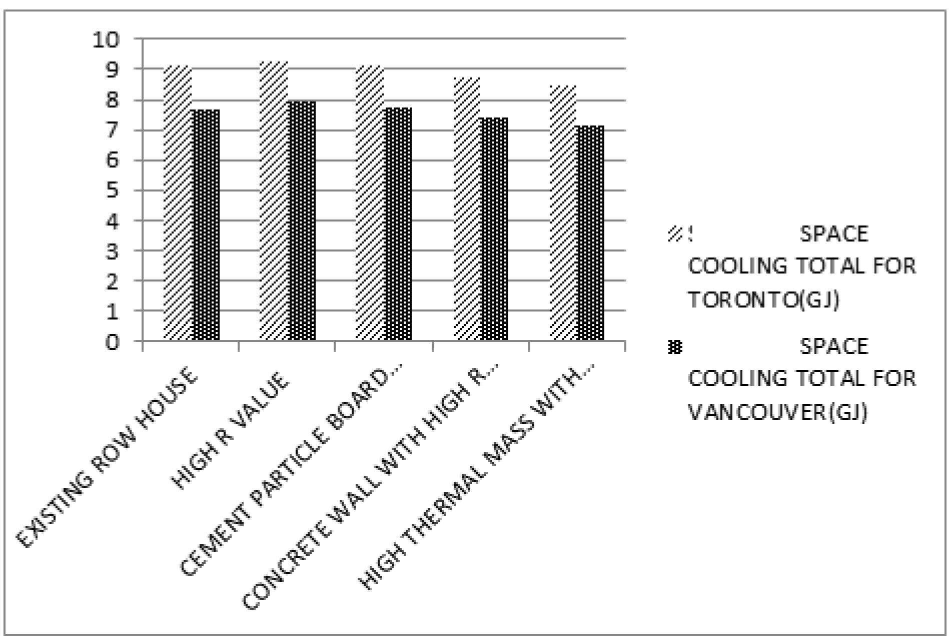




ROW HOUSE HEATING AND COOLING ENERGY ANALYSIS –

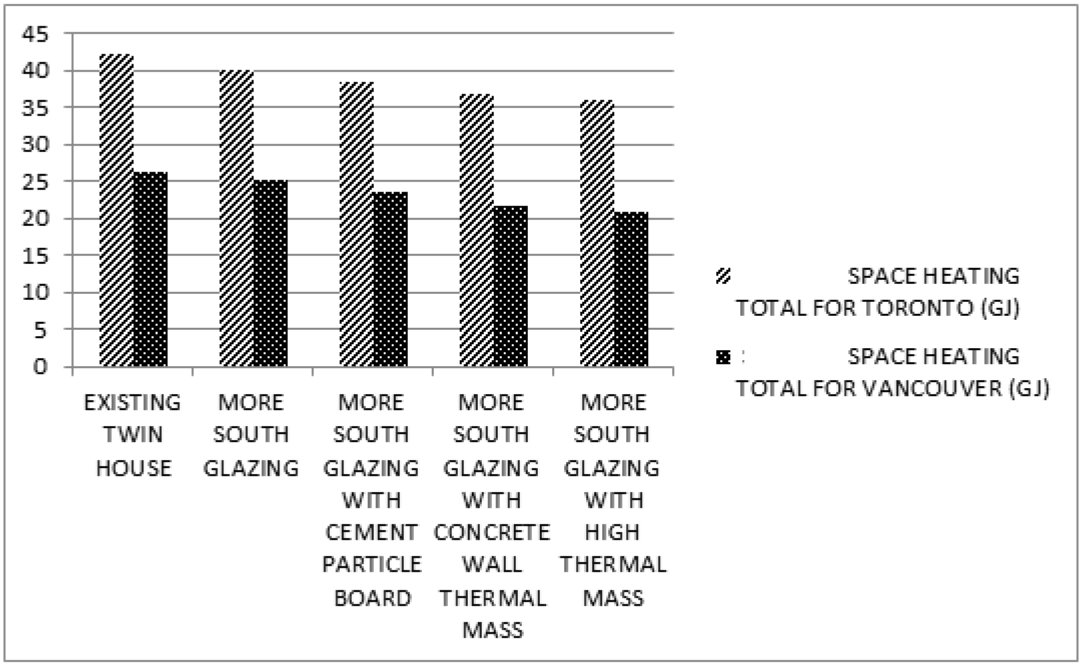
Insulation increased R value and Thermal Mass

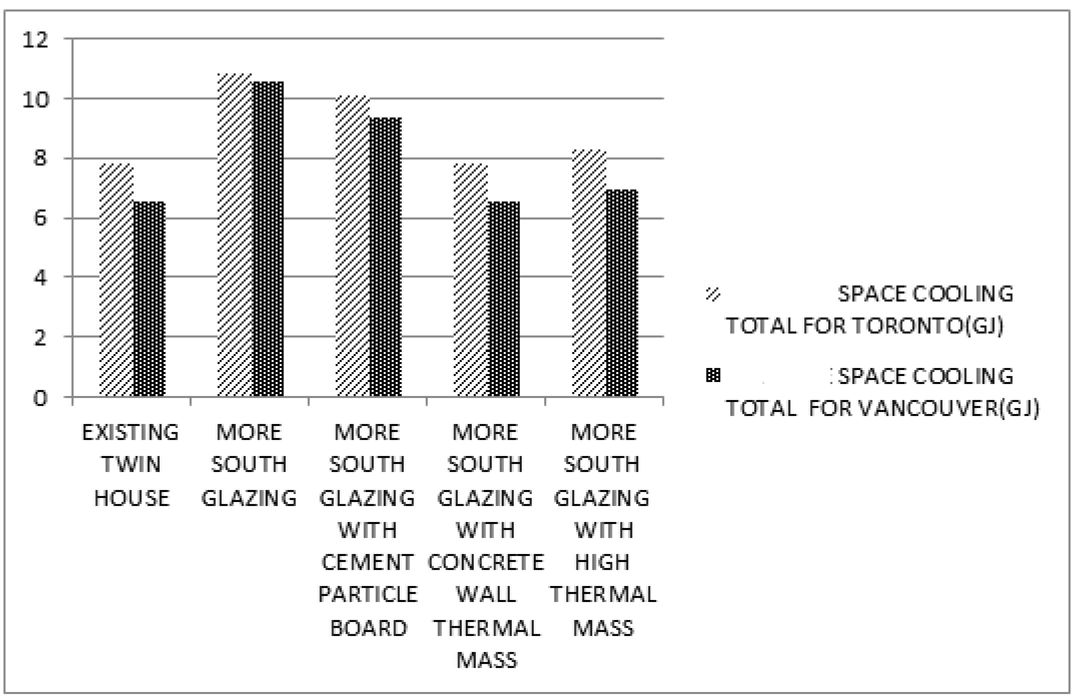




CCHT HEATING AND COOLING ENERGY ANALYSIS –

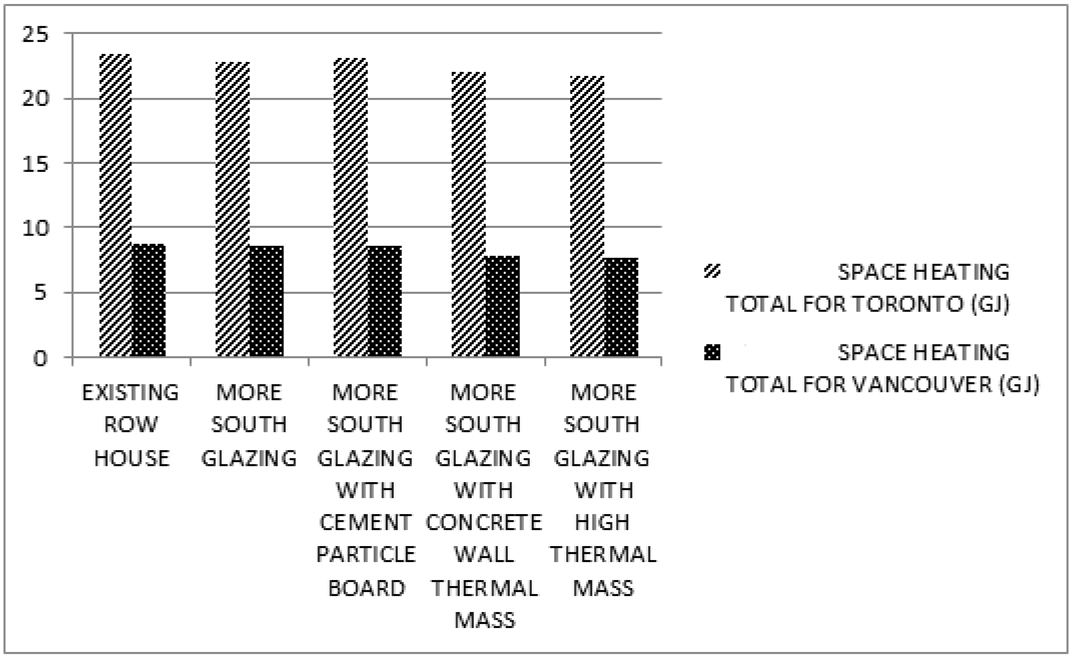
Increased south face glazing and Thermal Mass

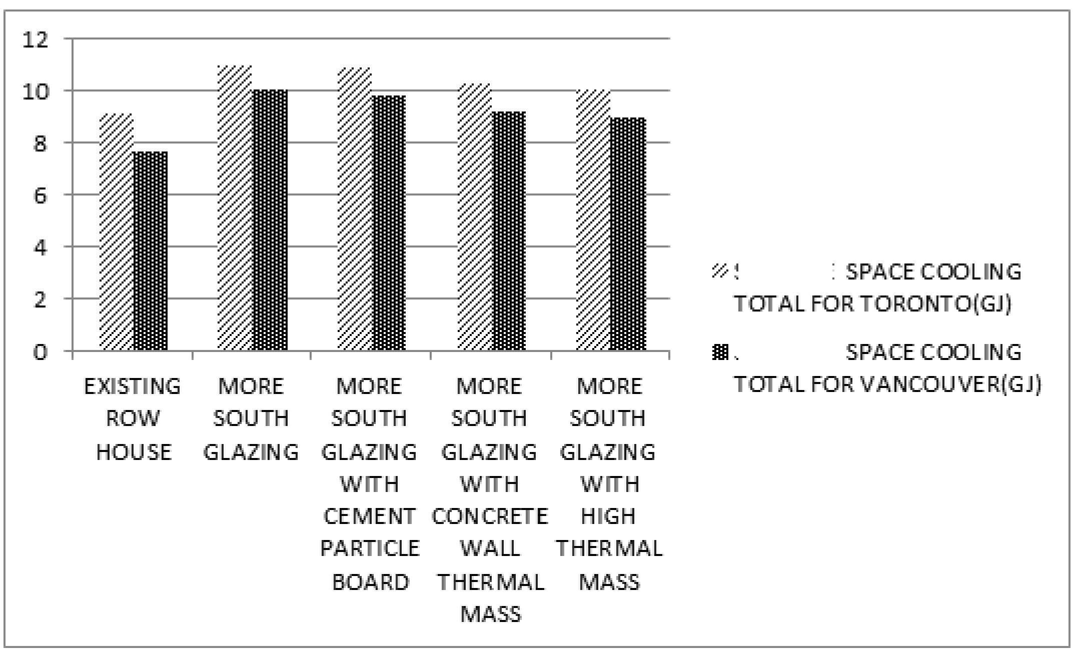




ROW HOUSE HEATING AND COOLING ENERGY ANALYSIS –

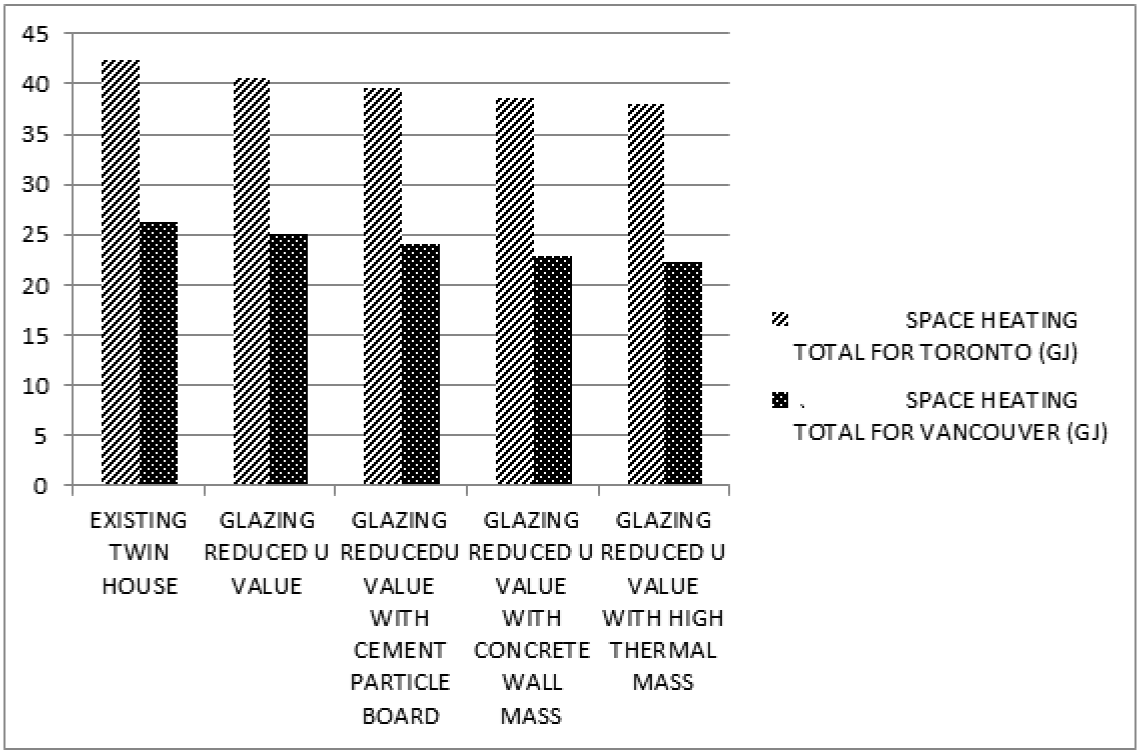
Increased south face glazing and Thermal Mass

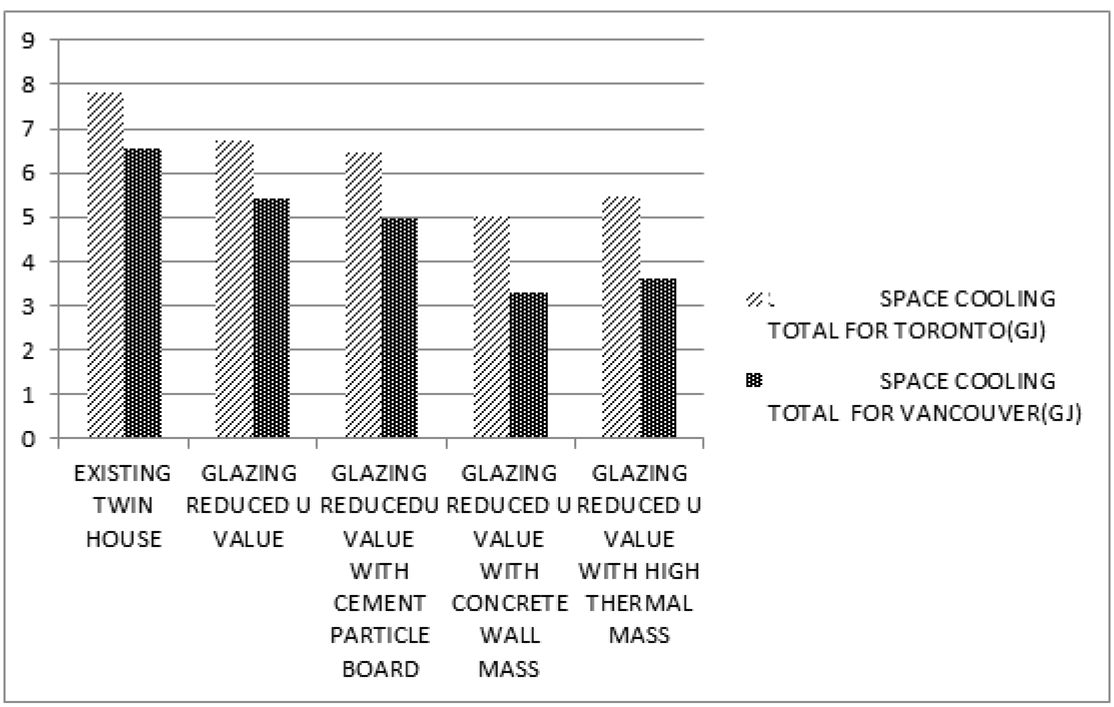




CCHT HEATING AND COOLING ENERGY ANALYSIS –

Glazing Reduced U value and Thermal Mass





ROW HOUSE HEATING AND COOLING ENERGY ANALYSIS –

Glazing Reduced U value and Thermal Mass