UTILIZATION OF THERMAL MASS IN THE TORONTO NET ZERO ENERGY HOUSE FOR THERMAL COMFORT AND ENERGY SAVINGS

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ABSTRACT

A detailed model of the Net Zero Energy Town House in Toronto is developed in TRNSYS. The incorporation of thermal mass into the building envelope has been demonstrated to contribute to the enhancement of occupant comfort through the reduction of indoor temperature fluctuations. It has also been shown to cause a decrease in the overall energy consumption associated with the heating and cooling of buildings. The incorporation of a variety of thermal mass such as a concrete slabs and phase change materials (PCM) into the building envelope is modelled. The impact of using the thermal mass on the indoor temperature and the overall heating/cooling loads is analyzed. Simulations are conducted for the summer and winter months to determine the potential reductions in the peak temperatures and daily temperature fluctuations. Hourly temperature profiles are analyzed to estimate the total number of hours that the indoor temperature falls or rises above the set point. The effectiveness of using phase change materials is contrasted with the use of thermal mass such as a concrete slab.

INTRODUCTION

Buildings are responsible for more than 30% of the total energy consumed in Canada [*SBRN, 2007*]. As the price of energy increases and concerns for sustainability and conservation grow, it has becomes essential to devise ways of reducing the overall energy use in buildings. The use of thermal mass incorporated into the building envelope has been found to be an effective way to reduce the heating and cooling loads. Furthermore, in climates where a large daily temperature fluctuation exists, the use of thermal mass has contributed to the lowering of the indoor temperature peaks and smoothing of the temperature fluctuations, thereby contributing significantly to the occupant comfort (*Kalogirou et al*., 2002).

Much of the work done previously on the use of thermal mass in buildings has been experimental in nature and has focussed mainly on conventional brick construction in hot climates such as Asia and Africa. This research will analyze the impact of using thermal mass with a building envelope that is highly insulated, and of a light construction, such as that used in Low Energy or Net Zero housing. Furthermore, this analysis would also evaluate the impact of using thermal mass in a cold climate such as that found in Canada

Thermal Mass is defined as any building material having a high heat storage capacity that can be integrated into the structural fabric of the building to effectively utilize the passive solar energy for the purposes of heating and cooling. Some of the commonly used materials include concrete slabs, bricks and ceramic blocks [*Shaw et al*., 1994]. The selection of a particular material to function as thermal mass depends on a variety of factors such as a high density (ρ), a high specific heat capacity (C_p) and the ability to delay the time taken to release the heat(*Kalogirou et al*.,2002). The time lag for some common building materials with a thickness of 305 mm is 10 hours for common brick, 6 hours for face brick, 8 hours for heavyweight concrete and 20 hours for wood (*Balaras*, 1996). The selection of a particular material depends upon the desired indoor thermal characteristics and the structural properties of the building envelope.

Most of the buildings and homes constructed in cold environments such as Canada and parts in the North East of the United States, are highly insulated and of a light construction with very little thermal mass. This is in contrast to buildings in Africa and Asia that are primarily designed for use in a hot climate and have concrete and other heavy materials as part of the building envelope (*Gregory et al.,* 2008). Thus most buildings in Canada and the US are prone to extreme temperature fluctuations and uncomfortable indoor conditions especially during the fall and spring seasons, when the heating and cooling is not in operation.

One aspect by which thermal mass proves to be more effective when compared to conventional insulation is its ability to delay the peak loads during the winter and summer seasons. In winter, any excess solar radiation that is stored by the building mass during the daytime is progressively released later during the evening, when the heating load can be significant. This can have a significant impact on the overall heating load of the building. *Kalogirou et al*. have shown a total reduction in heating load of 47% through the application of thermal mass in a south facing wall using TRNSYS. 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 drastically reduced by incorporating south facing walls with thermal mass. *Ruud et al.* (1990) demonstrated through the use of test chamber in Florida, the impact of using thermal mass causing a reduction of 18% in the cooling load during the day time. *Brown* (1990) conducted detailed simulations on an office building to determine the effect of varying the thermal mass. It was concluded that that an increase in thermal mass from 21 to 201 kg/m^2 of floor area, in closed and ventilated buildings, can reduce the peak indoor temperature by between 1°C and 2°C. *Ogoli.*, in tests conducted in Nairobi, Kenya, showed that thermal mass in the form of heavy concrete tile and timber panelling was able to maintain the indoor temperature within the comfort zone of around 25°C, when the outdoor temperature hovered around 33°C. The location of thermal mass within the building envelope is also very important. *Balaras* (1996) has determined that it is more effective when the thermal mass is placed in between the insulation. It can also be placed on the outside of the building envelope thus providing direct exposure to the solar radiation Furthermore, the orientation of the thermal mass within the building is essential ,as it dictates the time delay of the temperature peaks. North and east facing building envelopes have little need for a time delay. For the building envelopes facing the south and west directions respectively, an 8h time lag is sufficient to delay heat transfer from midday until the evening hour [*Ogoli,* 2003].

MODEL/METHODOLOGY

In order to conduct detailed simulations and analyses of the impact of using thermal mass, a detailed model of the Net Zero House located in the downtown area of Toronto, ON is developed in TRNSYS. The concept behind a Net Zero or Low Energy house is the design of thermal and structural systems for a residential unit in a manner that minimizes the energy consumption with the aim of making the house energy self sufficient . This is achieved through the use of high quality insulation materials and the utilization of renewable energy technologies such as PV and Geothermal for production of energy. The townhouse has a covered area of 210 m^2 and the orientation of the house is 37° West of South. The orientation and location of the houses have optimized to ensure that a maximum amount of solar energy can be captured to operate the Photovoltaic and PV Thermal panels for the generation of electricity and hot water respectively for the house. A ground source heat pump is also utilized during the winter to provide a reliable and efficient source of heating. Figure 1 shows a computer generated 3-D model of the house, with the solar panels oriented at 37° West of South .The building envelope of the Net Zero House is designed with the intention of minimizing the heat transfer to the outside.

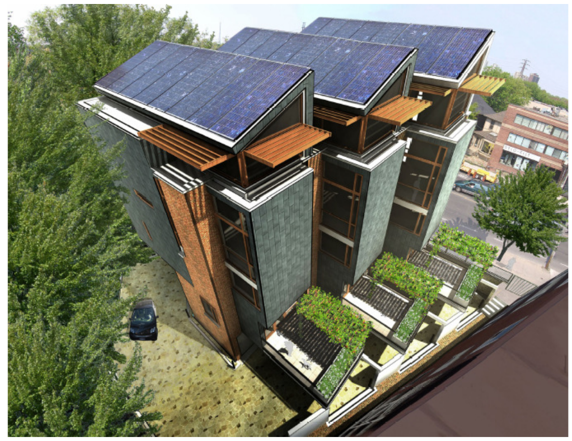

Figure 1: 3-D Computer graphic of one of the 3 twin Toronto SUI Net Zero Energy Town houses.

The external walls have been insulated with sprayed polyisocynurate foam insulation, which provides an overall insulation value of R-60. Roof assembly consists of drywall on 19 x 19 mm furring and 0.15 mm polyethylene vapour retarder attached to the bottom of the 294 mm pre-engineered I-joists. Sprayed polyisocyanurate foam is applied between joists as roof insulation. The roof has an insulation value of R-76. Table 1 shows the various layers used within the building envelope. The windows used have low emissivity are argon filled with a fibreglass frame have an insulation value of R-4 value. Walls below grade are of the insulating concrete form and have a 2.5 in of rigid polystyrene board with a waterproof membrane. The overall insulation value of the below grade wall is R-35.

SIMULATION PARAMETERS

A variety of simulations are conducted in TRNSYS to illustrate the impact of using thermal mass with the Net Zero house. TRNSYS is a modular simulation program, based on the FROTRAN programming language. It utilizes standalone components and mathematical modules for a wide variety of applications such as Heat Pumps and PVs etc in a user-friendly graphical interface. Each of these components can be connected together and represents the flow of information during the simulation.. The TRNSYS engine calls the system components based on the input file and iterates at each time-step until the system of equations is solved. Weather data is needed to perform the simulations with TRNSYS. TRNSYS runs through hourly values of various weather parameters included in a typical meteorological year (TMY) file. The weather file included with TRNSYS contains detailed weather data for thousands of locations around the world [*Klein et al.,* 1998].

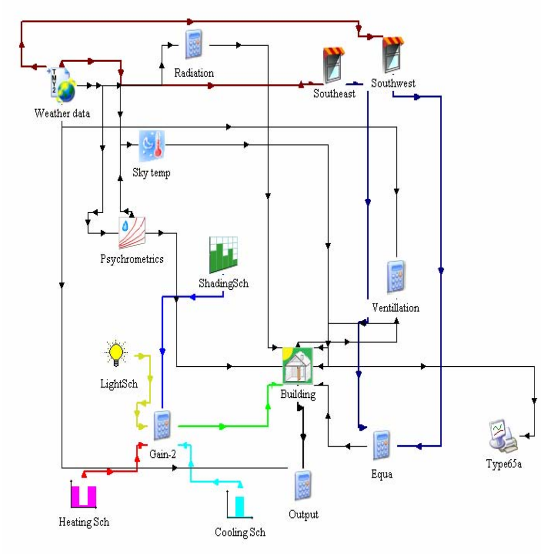

Figure 2: TRNSYS Model of the Net Zero Energy House.

For the particular case study on the Net Zero house, the weather data for the city of Toronto is used. For each of the different scenarios, the simulations are run for one year with a time step of one hour to ensure that the results are accurate. The simulations are run with the heating and cooling set points at 21°C and 25ºC respectively,which means that there is a complex interaction of heat transfer between the incident solar radiation, thermal mass and the heating/cooling equipment. The house consists of 5 zones which represent the garage, 1st floor, 2nd floor, 3rd floor and mezzanine. As a means of comparison all of the results are shown for either the 2nd floor or the 3rd floor or the mezzanine, since these are locations where the temperature peaks and fluctuations are expected to be the greatest.

PCM MODELLING

For modelling phase change materials, a Type 204 PCM component is utilized. The TYPE 204 component was developed in FROTRAN and integrated to TRNSYS by a team based at the Helsinki University of Technology (Lamberg, 2003). Utilizing the finite difference method with a Crank-Nicholson scheme, the model simulates heat transfer through a 3-D PCM composite wall component containing a total of 729 node (9 nodes in each direction).At each node, the conduction, convection and radiation heat transfer, along with the temperature is calculated (Ahmad et al, 2006). The 3-D wall element can be defined precisely to specify the concentration and melting points of the PCM used. The properties of the composite building material used in conjunction with the PCM can also be easily defined. To account for the changes in specific heat capacity of the PCM due to temperature variations, the model uses the effective heat capacity method to define the heat capacity at each phase, i.e liquid or solid.

For the purposes of the simulation, a commercial phase change material product by the name of MICRONAL DS 5008 is utilized. The relevant thermal properties of this material are modelled in TRNSYS using the Type 204 component. Manufactured by BASF, the PCM is composed of microscopically encapsulated plastic spheres containing a wax medium. It has a melting temperature of between 23ºC-25ºC and a latent heat of 110 kJ/kg (BASF,2008). This product would be integrated with gypsum wallboard, having a thickness of 25mm, to ensure a uniform distribution of PCM throughout the building material

Table 1
Wall layer used with the Toronto Net Zero Energy House.

Gypsum Board (Dry Wall), 13mm
19 x 19mm Furring
Polyethylene Vapour Retarder, 0.15mm
(2x6) Wood Studs @600mm (24") O.C
Sprayed Polyisocyanurate closed cell foam 139mm RSI-6.5
OSB Structural Sheathing with STO Gold Coat 13mm
Rigid insulation-Extruded Polystyrene 100mm. (R-20)
Air space 25mm
Face Brick 100mm

SIMULATION/RESULTS

The use of concrete slab of varying thickness and PCM is modelled as thermal mass through the addition of these layers to the building envelope of the house. Yearly simulations are conducted to analyze the impact of using thermal mass during both the summer and winter months. In a highly insulated house of a light weight construction such as the one modelled in this paper, one of the key factors impacting the comfort of the occupants is the fluctuations in the indoor temperature caused by interplay of a variety of factors such as the incident solar radiation, HVAC system and heating/cooling set points etc. During the winter months, overheating of the indoor environment is a major concern, especially on a clear, sunny day, where the house is exposed to direct incident radiation. These solar gains, when combined with the regular winter heating capability, dramatically exacerbate the degree of discomfort for the occupant. This effect is further compounded for portions of the building that have a large window area.

The use of thermal mass integrated with the building envelope is an effective method that can be adopted to increase the indoor thermal comfort by reducing the degree of overheating during the winter.A strategically placed unit of thermal mass, such as a concrete slab, within the building envelope can not only minimize the indoor temperature fluctuations, but also contribute to a reduction in the cooling load of the building. This is achieved through the storage of any unwanted solar gains during the day, and the subsequent release of this energy during the evening when the temperature drops.

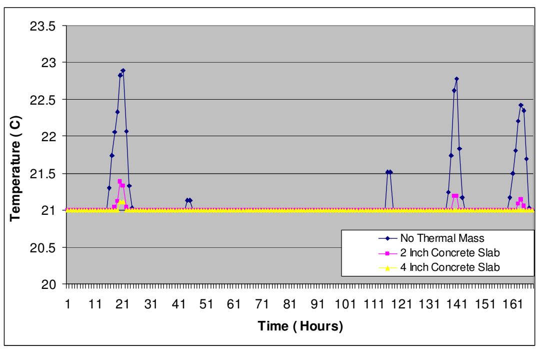

Figure 3: Temperature profile of the Mezzanine floor of the Net Zero Energy house during a typical winter week with varying thermal mass

Figure 3 illustrates the impact of using a concrete slab with varying thickness as thermal mass, for mitigating the occasional indoor overheating experienced by occupants. Results are presented for a typical winter week for the mezzanine floor. It can be observed that during the week, the indoor temperature occasionally exceeds the heating set point of 21ºC for a few hours. This could occur on a clear sunny day, where the incoming solar radiation incident on the windows, exceeds the heat loss through the building envelope. The impact of using the 2-inch and the 4-inch concrete slabs can be seen by comparing the peak indoor temperatures, which remain below 21.5ºC throughout the week, as opposed to temperatures which rise to 23ºC when no thermal mass is used.

Despite the fact, that the mezzanine floor has only approximately 20% of its facade area comprised of glazing and thus exposed to the incident solar radiation, there were occasional periods where the temperature rose above 21ºC. This situation is in

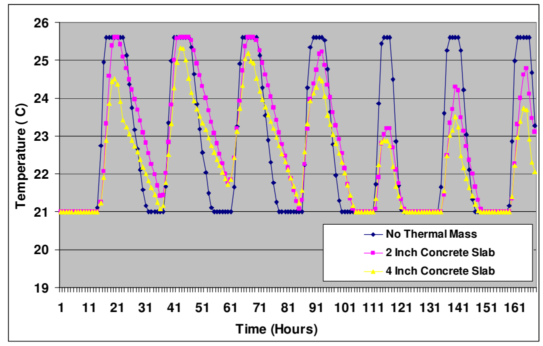

Figure 4: Temperature profile of the 3rd floor of the Net Zero Energy house during a typical winter week with varying thermal mass

contrast to the 3rd floor which has almost 80% of its facade area covered with the windows. Therefore, there can be an expectation that the indoor temperature would fluctuate much more than what was observed on the mezzanine floor. This is observed in figure 4. The 4-inch concrete slab significantly reduces the peak indoor temperatures during the week, while towards the end of the week, the impact of the temperature reduction is further magnified with both the 2-inch and 4-inch concrete slabs. Because of the presence of a large window area, even with thermal mass present, the indoor temperature of the 3rd floor rises beyond the heating set point. One way this could be controlled would be through the use of additional thermal mass or by lowering the heating setpoint.

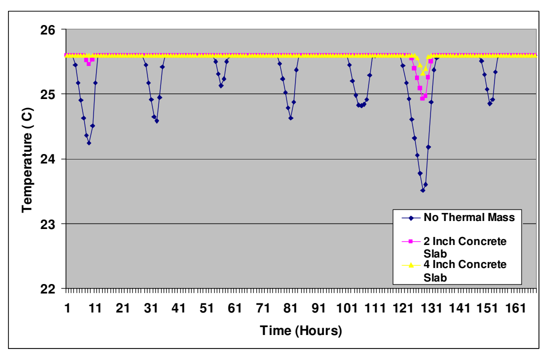

Figure 5: Temperature profile of the Mezzanine floor of the Net Zero Energy house during a typical summer week with varying thermal mass

The impact of thermal mass was also analyzed for both the mezzanine and 3rd floor of the house for the summer season and the results are presented in figures 5 and 6 respectively. As can be observed from these figures, the presence of thermal mass ensures that the temperature is maintained within a comfortable range of the cooling set point. From Figure 5, it is seen that the indoor temperature remains constant in response to a drop in the ambient temperature and incident solar radiation, when thermal mass is utilized. This is in contrast to a drop in the indoor temperature when no thermal mass is present. It is obvious that during the summer there is a possibility of over-cooling the building when little or no thermal mass is present, thereby increasing the cooling requirements. During a typical summer day, the cooling equipment in the building ensures that the temperature is maintained within a comfortable range. However, as the temperature and the solar gain decrease during the evening, a building with adequate thermal mass is better able to resist any sharp downward fluctuations in temperature. Figure 6 shows a similar phenomena but with a much more visible trend showing the impact of thermal mass.

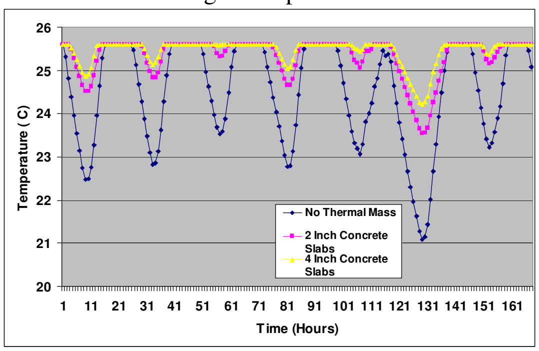

Figure 6: Temperature profile of the 3rd floor of the Net Zero Energy house during a typical summer week with varying thermal mass

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The use of phase change materials over ordinary thermal mass such a concrete slab has several advantages, with the primary benefit being the higher storage density. It has been found that a 1.5 cm thick wallboard of Micronal PCM has the same storage capacity as 12 cm thick brick or a 9 cm concrete slab (BASF, 2007). Simulations were conducted to compare and contrast the use of Micronal PCM with ordinary concrete slab as thermal mass. The results are presented in Figure 7, whereby the concentration of Micronal PCM within the outer layer of the building envelope is 20%

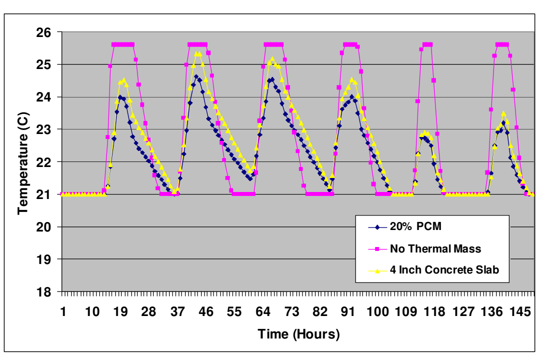

Figure 7: Temperature profile comparing the thermal mass effect of 20% Micronal PCM and 4-Inch Concrete Slab for the 3rd floor of the Net Zero Energy house during a typical winter week.

As Figure 7 illustrates, the Micronal PCM provides a much better resistance to winter overheating experienced on the 3rd floor, when compared with the 4-inch concrete slab. This means that using the 4-inch concrete slab as a substitute for Micronal PCM should provide acceptable results and cost savings depending on the scope of the application. It is interesting to note that in addition to the reduction in peak temperature as a result of using thermal mass, there is also a reduction in the total duration of the peak temperature. From Figure 7, it is seen that once the peak temperature has been achieved, it remains at that level for a few hours. This is in contrast to a sharp drop in the temperature after the peak has been achieved when thermal mass is utilized.

Table 2
Yearly heating and cooling loads as a result of varying thermal mass.

Scenario	Heating Load (kWh)	Cooling Load (kWh)
Base Case (No Thermal Mass)	5511	3681
2-Inch Concrete Slab	5271	3429
4-Inch Concrete Slab	4895	2902
20% Micronal PCM	4846	2861

The impact of using thermal mass in terms of the total yearly energy savings is presented in Table 2. As is obvious, there is a progressive decrease in the annual heating and cooling loads as the quantity of thermal mass is increased. The total savings in the cooling load are between 5-7 % and 8-15 % for the heating and cooling loads respectively. Annual Energy consumption for the 4-inch concrete slab and 20% Micronal yield almost similar results. This further validates the conclusion regarding the similarity of the heat storage capacity of the 4-inch concrete slab and 20% Micronal PCM, as established by Figure 7.

Table 3
Total number of hours during the winter season, the indoor temperature overheats to the cooling set point, 25ºC.

Part of the House	No Thermal Mass	2-Inch Concrete Slab	4-Inch Concrete Slab
3rd Floor	602 hours	386 hours	273 hours
2nd Floor	454 hours	377 hours	323 hours
Mezzanine	161 hours	109 hours	92 hours
1st Floor	290 hours	234 hours	207 hours

Another metric that is of importance to the comfort of the occupants is the frequency of the temperature deviation from the set points. During the winter season, the temperature frequently rises above the heating set point as result of solar gains. This would not contribute to occupant discomfort as long as the temperature is below the cooling setpoint. Characteristics such as these are tabulated and presented in Tables 4, encompassing different areas of the Net Zero Energy House. As the results show, parts of the house that are exposed to direct solar gain experience much more benefits from thermal mass than other portions of the house. As an example, on the third floor, the total number of hours when the indoor temperatures reaches the cooling set point is reduced to only 386 hours from 602 hours when a 2-inch concrete slab is added to the building envelope. The results on the 1st and 2nd floor are not as significant when compared to the 3rd floor and the mezzanine. Table 4 presents the total number of hours that the indoor temperature exceeds the heating set point of 21ºC.

Table 4
Total number of hours during the winter season, the indoor temperature exceeds the heating set point, 21ºC.

Part of the House	No Thermal Mass	2-Inch Concrete Slab	4-Inch Concrete Slab
3rd Floor	1603 hours	1186 hours	1039 hours
2nd Floor	653 hours	577 hours	523 hours
Mezzanine	358 hours	299 hours	255 hours
1st Floor	477 hours	394 hours	368 hours

The influence of the insulation level on the heating/cooling load was also investigated, with a goal of determining if excessive insulation was causing overheating during the winter and thus increasing the cooling load.

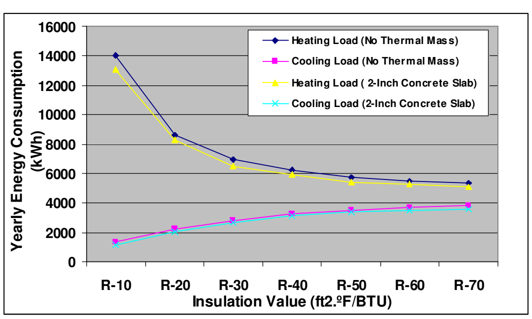

Figure 8: Comparison of the impact on the heating and cooling loads as insulation levels are varied when thermal mass is used versus no thermal mass

It is seen from Figure 8 that increasing the insulation level, decreases the heating load as would be expected, but there is a corresponding increase in the cooling load as result of this. This can be attributed to the higher levels of insulation trapping the heat in the building, and the problem further exacerbated by the unwanted solar gains. Simulations are also conducted for similar insulation levels, but with added thermal mass in the form of a 2-inch concrete slab. The results show lower heating and cooling loads when thermal mass is presented, as the insulation levels are modified.

Figure 9 presents the results of the yearly simualtion for the mezzanine floor, comparing the impact of using a 4-inch concrete slab as thermal mass. It is obvious that using thermal mass not only provides a comfortable indoor environment during the summer and winter seasons by reducing the temperature peaks but it also reduces the energy consumption loads.

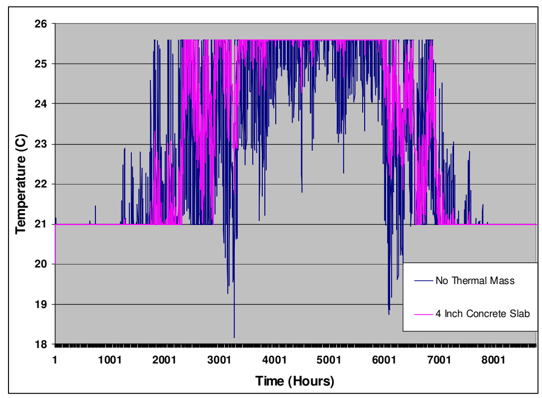

Figure 9: Yearly temperature profile of the Mezzanine Floor of the house comparing the impact of using a 4-inch thick concrete slab.

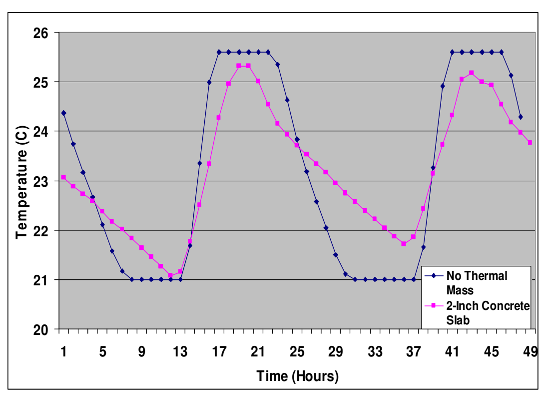

Figure 10: Temperature profile of the 3rd Floor of the house for a 48-hour duration for the winter season,, comparing the impact of using a 4-inch thick concrete slab

Figure 10 illustrates the temperature profile for the 3rd floor for a period of only 48 hours. The objective is to illustrate some key benefits of using thermal mass. In addition to the reduction in the temperature peaks and fluctutations, there is also a shift in when the peak temperature occurs and the duration that it lasts for. Referring to Figure 10, it observed that for the temperature peaks at 25ºC and remains at the level for 4-5 hours. This is contrasted with a peak temperature that lasts at most 1-2 hours when a 2-Inch concrete slab is used.

CONCLUSION

This paper was an attempt to demonstrate the impact of using a variety of thermal masses on the Toronto Net Zero Energy house with a lightweight construction and a highly insulated building envelope. It was found that the use of thermal mass with the Net Zero Energy house in Toronto provides reasonable results in terms of the reductions in the daily indoor temperature fluctuations along with a decrease in the annual heating and cooling loads. The problem of overheating during the winter was also addressed effectively with PCM and concrete slabs as thermal mass. The effectiveness of Micronal PCM was also compared to ordinary thermal mass such as a concrete slab and was found to yield similar results in terms of the total energy consumption. the frequency of the temperature deviation from the cooling and heating set points were also determined and it was found that thermal mass is the most effective when a particular portion of the house is exposed to direct solar radiation. The relationship between the insulation level and its contribution to the heating load was also established and it was determined that reducing the level of insulation would decrease the cooling load.

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