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The Study of Thermal Mass as a Passive Design Technique for Building Comfort and Energy Efficiency

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Abstract: The day/night (diurnal) changes in temperature and solar radiation pose challenges for maintaining human thermal comfort in buildings. Passive and energy-conserving buildings seek to manage the available thermal energy by lowering peaks and dampening the fluctuations in order to maintain conditions for human comfort. Appropriate use of thermal mass moderates the internal temperatures by averaging diurnal extremes. Thermal mass is one of the powerful tools which architects and designers can use to control temperature. It can be used to optimize the performance of energy-conserving buildings that rely primarily on mechanical heating and cooling strategies. Massive building envelopes-such as masonry, concrete, earth, and insulating concrete forms (ICFs) can be utilized as one of the simplest ways of reducing building heating and cooling loads. This article analyses the role and effectiveness of thermal mass as a strategy for providing indoor thermal comfort for passive solar and energy conserving buildings.

Key words: Thermal mass, passive solar, building comfort, energy efficiency.

1. Introduction

Thermal mass is a concept in building design which describes how the mass of the building provides "inertia" against temperature fluctuations, sometimes known as the thermal flywheel effect. For example, when outside temperatures are fluctuating throughout the day, a large thermal mass within the insulated portion of a house can serve to "flatten out" or dampen the daily temperature fluctuations, since the thermal mass absorbs heat when the surroundings are hotter than the mass, and give heat back when the surroundings are cooler. This is distinct from a material's insulative value, which reduces a building's thermal conductivity, allowing it to be heated or cooled relatively separate from the outside, or even just retain the occupants body heat longer [1].

Thermal mass is particularly beneficial where there is a big difference between day and night outdoor temperatures especially in hot dry climate. Appropriate use of thermal mass moderates internal temperatures by averaging day/night (diurnal) extremes. When used judiciously, thermal mass can delay heat flow through the building envelope by as much as 10 to 12 hours producing a warmer house at night in winter and a cooler house during the day in summer. Thermal mass is effective in improving building comfort in any place that experiences these types of daily temperature fluctuations—both in winter as well as in summer. When combined with passive solar design, thermal mass can play an important role in providing major reductions in energy use for active heating and cooling systems.

The reason for this is that in summer, heavy external walls delay the heat transfer from the outside into the inside spaces. Moreover, if the building has a lot of internal mass the increase in the air temperature is slow. This is because the penetrating heat raises the air temperature as well as the temperature of the heavy thermal mass. The consequence is a slow heating of the building in summer and the maximal inside temperature is reached only during the late hours when the outside air temperature is already low. The heat that flows from the heavy walls inside can be removed with good ventilation in the evening and night. The

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capability to store energy also helps in winter, since energy can be stored in walls from one sunny winter day to the next cloudy one [2].

2. Building Elements Characteristics

Structural elements of a building usually consist of more than one material. For instance, a simple brick wall usually has a plaster layer on both sides of it. A typical reinforced concrete roof has a plaster layer underneath and various waterproofing layers above it. The properties of the building element are then derived from the thermo-physical properties of different material layers. Three of these properties are important in the present context. The U-value of an element is its conductance for heat and it depends upon the thermal conductivity of the materials and the thickness of the different layers. For composite elements the U-value is the inverse of the sum of the resistances of the individual layers. Air to air U-values also take into account the resistance between the building element surfaces and the surrounding air and are a useful measure of the heat conducted by the building element under steady-state conditions [3].

When building elements are subjected to temperature fluctuations, not only the heat transmitted by the element but also the time taken for heat to travel through the element becomes important. A fluctuating temperature wave outside the building element, gives rise to another temperature wave with lower amplitude on the inside. The two temperature waves are out of phase by an angle called time lag, which depends upon the thermal "diffusivity", and thickness of the building element. The thermo-physical properties of commonly used building materials are given in Table 1.

Time lag is given by the difference in hours between the occurrence of the peak temperature outdoors and the corresponding peak temperature indoors (Fig. 1). The ratio of the amplitude of internal temperature wave to the amplitude of external temperature wave is called the "decrement factor". Massive building elements such as brick walls usually have a large time lag and lower decrement factor than thinner elements of lightweight materials [4].

Table 2 shows time lag figures for a variety of building materials. In cool climates where significant heating is necessary and adequate solar gains cannot be relied to keep overnight temperatures stable, insulation of exposed external walls is warranted.

3. Effect of Thermal Mass on Interior Temperature

The ability to store energy in a thermal mass is a vital strategy in controlling and ameliorating the building microclimate and lowering energy demand heavily weighing on the infrastructure. Rising living standards on the one hand, and the environmental implications of increased fossil fuel exploitation on the other hand, indicate the need for alternative solutions, and a more sane use of energy in buildings. High thermal capacity in a shaded and insulated building can help lower indoor maxima by 35-45% of the outdoor ones when the building is unventilated [6].

In a study done by Shaviv, an analysis for the determination of the reduction in the maximum indoor temperature compared with the maximum outside temperature (Tmax) was carried out using an hourly simulation model ENERGY to predict the thermal performance of the building. The results obtained show

Table 1 Comparison of thermal and physical properties of commonly used materials.

Material	Density (kg/m^3)	Thermal conductivity (W/m ℃)	Specific heat (kJ/kg ℃)	Thermal Storage (kJ/m^3 ℃)
Adobe	1730	0.516	1.00	1.73
Stone	2451	1.800	0.92	2.26
Reinforced concrete	2400	1.728	0.96	2.30
Hollow clay block	1029	0.360	0.84	0.86
Hollow cement block	1403	0.600	0.84	1.18
Solid cement block	1600	0.789	0.84	1.34
Thermal insulation material	32	0.027	0.66	0.02

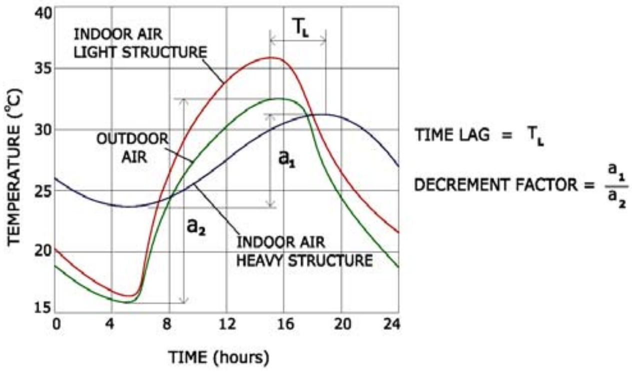

Fig. 1 Effect of thermal capacity of building on time lag and decrement factor.

Table 2 Time lag figures for various materials (Baggs, SA, JC, DB., 1991) [5].

Material (thickness in mm)	Time lag (hours)
Insulated Brick Veneer	5.0
Concrete (250)	6.9
Double Brick (250)	7.0
AAC (200)	7.0
Adobe (250)	9.2
Rammed Earth (250)	10.3
Compressed Earth Blocks (250)	10.5

that in the hot humid climate, it is possible to achieve a reduction of 3–6 ℃ in a heavy constructed building without operating an air conditioning unit. The exact reduction achieved depends on the amount of thermal mass, the rate of night ventilation, and the temperature swing of the site between day and night [7].

Hasan Fathy conducted tests on experimental buildings located at Cairo Building Research Centre, using different materials. The materials used were mud brick walls and roof 50 cm thick and prefabricated concrete panel walls and roof 10 cm thickness. The thermal performance of the two buildings over a 24 hour cycle was monitored. The air temperature fluctuation inside the mud brick model did not exceed 2℃ during the 24 h period, varying from 21-23℃ which is within the comfort zone. On the other hand, the maximum air temperature inside the prefabricated model reached 36℃, or 13℃ higher than the mud brick model and 9℃ higher than outdoor air temperature. The indoor temperature of the prefabricated concrete room is higher than the thermal comfort level most of the day [8]. Moore [9] reported the temperatures in and around an adobe building. It indicated that when the average inside and outside temperatures are about equal, the maximum interior temperature occurred at about 22:00 h (about 8 h after the outside peak). Furthermore, the outside temperature swing was about 24℃ while the interior swing was about 6℃ [9]. The effect of thermal mass on interior temperature is shown in Fig. 2.

4. Ideal Thermal Mass

There is no single material which has all the desirable structural and thermal properties. Combinations of materials with different properties are used to provide the necessary properties in an element. In order to be effective as a thermal mass, a material must have a high heat capacity, a moderate conductance, a moderate density, and a high emissivity. It is also important that the material serve a functional (structural or decorative) purpose in the building. Among common building materials, wood does not make a good thermal mass because it not only has a low heat storage potential, but is also not very conductive. Rammed earth provides excellent thermal mass because of its high density, and the high specific heat capacity of the soil used in its construction.

Concrete and other masonry products are ideal, having a high capacity for heat storage, moderate conductance that allows heat to be transferred deep into the material for storage, high emissivity to allow absorption of more radiation than that which is reflected. When sized properly, concrete is effective in managing diurnal energy flow. Conveniently, structural concrete and thermal mass share common dimensions, so there is no wasted mass when building a structure. Insulating concrete forms are commonly used to provide thermal mass to building structures. Insulating Concrete Forms or ICF provide the specific heat capacity and mass of concrete. Thermal Inertia of the structure is very high because the mass is insulated on both sides. Water is also effective as a thermal mass

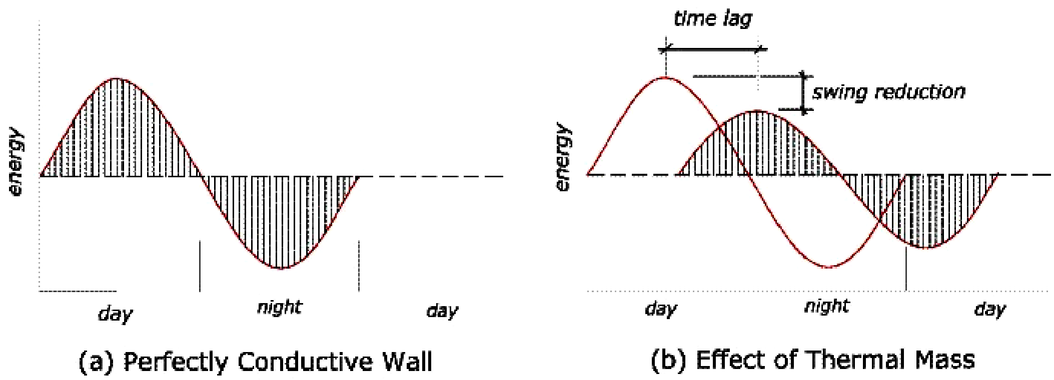

Fig. 2 Effect of thermal mass on interior temperature.

in that it has high potential for heat storage and it can be effective in a diurnal thermal management scheme.

Steel, while having a seemingly high potential for heat storage, has two drawbacks–its low emissivity indicates that a large majority of the incident radiation is reflected, rather than absorbed and stored, and its high conductivity signals an ability to quickly transfer heat stored in the material’s core to the surface for release to the environment, thus shortening the storage cycle to minutes rather than the hours needed for diurnal thermal tempering. Glass also seems to have a high potential for heat storage, but it is relatively transparent to near infrared radiation and reflective of far infrared radiation. Adding pigments to glass (especially blue and green) increases its ability to absorb radiation, which can become a thermal problem during the cooling season.

5. Effectiveness of Thermal Mass in Hot and Arid Climates

One of the common occurrences of large parts of the Middle Eastern deserts is the hot spells. During summer these outdoor conditions may become unbearable in a matter of hours. This, in turn, may create indoor conditions that are even worse. Combined with dust storms, such hot spells may even prevent the use of outdoor spaces and the opening of windows to allow for comfort ventilation. Thermal mass provides probably the best–sometimes the only–solution, especially considering the possibility of power failures due to the storms or excess peak energy demand. Alternately, when such spells occur during the winter, thermal mass is able to take advantage of the high air temperatures and store heat [10].

In hot and dry climates with a large diurnal range it is advantageous to use massive building elements. The effect of massive construction is to lower the maximum internal daytime temperature and to raise the minimum nighttime temperature while in lightweight construction; the internal temperatures follow closely the pattern of outdoor temperatures (Fig. 2). Masonry construction provides heat storage within the building structure due to its thermal capacity, which helps contain indoor temperature fluctuations and acts as interim heat sink. The importance of heat storage increases with larger swings in outdoor temperature. Heat dissipation is then achieved overnight by exposing the building structure to the cooler night-time outdoor air.

The classical use of thermal mass includes adobe or rammed earth houses. Its function is highly dependent on marked diurnal temperature variations. The wall predominantly acts to retard heat flow from the exterior to the interior during the day. The high volumetric heat capacity and thickness prevents heat from reaching the inner surface. When temperatures fall at night, the walls re-radiate the heat back into the night sky. In this application it is important for such walls to be massive to prevent the ingress of heat into the interior.

6. Conclusions

Thermal mass is an essential strategy for indoor climate control especially in hot dry climates. Indoor comfort temperatures may be achieved by proper application of the thermal mass. In addition, energy can be saved if an air conditioning unit is used [11]. It has the potential to ameliorate indoor extremes as well as energy conservation in conditioned buildings. In certain climates, massive building envelopes-such as masonry, concrete, earth, and insulating concrete forms (ICFs)-can be utilized as one of the simplest ways of reducing building heating and cooling loads. Such reductions in building envelope heat losses combined with optimized material configuration and the proper amount of thermal insulation in the building envelope help to reduce the building cooling and heating energy demands and building related CO_2 emission into the atmosphere. Having been traditionally considered as appropriate for housing in hot dry climates, its advantages are being reassessed for free running buildings as well as for lowering energy consumption in conditioned ones, in a wide variety of climates and building types [12].

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