The Role of Thermal Mass in Low-Slope Roof Design

By Thomas J. Taylor, PhD

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Thermal mass affects the dynamic flow of heat into or out of buildings. While important, it has not received as much attention as thermal resistance.

Building codes continue to increase thermal insulation requirements as the primary method to improve the thermal efficiency of building enclosures. For example, the *International Energy Conservation Code* (IECC) only specifies thermal insulation in its prescriptive requirements and does not consider the possible importance of thermal mass.[1] Building codes in the United States rely on the IECC and the related American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) 90.1 standard[2] for energy efficiency requirements. As noted by D'Orazio et al.,[3] the European Directive 2002/91 on the energy performance of buildings,[4] which is used by many current European Union member states, also overlooks the importance of thermal mass.

In standard practice, building designs also tend to focus only on the thermal resistance of the building enclosure and typically do not consider thermal mass. This practice is convenient because, conceptually, thermal resistance is readily understood and measured, and its effects are easily calculated. However, thermal resistance is a steady-state property, and the thermal performance of building enclosures has been shown to be affected by thermal mass and other related properties (for example, see a review and analysis of the topic by Kossecka and Kosny[5]).

According to extensive reviews of the topic by Verbeke,[6] Verbeke and Audenaertad,[7] and Olsthoorn et al.,[8] much of the prior research on thermal mass focused on the effect of having greater thermal mass in floors and walls, with little work having been done on roofs. In a field study of the effect of thermal mass of roofs, D'Orazio and colleagues[3] examined occupants' thermal comfort when the thermal mass of residential roofs was changed. Furthermore, many studies cited in the reviews by Verbeke, Verbeke and Audenaertad, and Olsthoorn et al. used qualitative descriptions of thermal mass such as low, medium, and high without providing data that could be used by a building designer looking to quantify the effects of various possible designs.

While much prior work has examined wall design, it should be noted that low-slope roofs are particularly susceptible to the diurnal—that is, the daily cycle—effects of the sun. In urban areas, the roof may be a smaller part of the total exterior building area; however, in suburban regions, that is not always the case. In the United States, big-box construction of warehouses and large retail outlets is dominated by large-area, single-story designs. For example, Walmart stores range between 2800 and 20,500 m^2 (30,000 and 221,000 ft^2) and Costco stores between 6800 and 19,000 m^2 (73,000 and 205,000 ft^2) with a typical size being 11,500 m^2 (124,000 ft^2).[9]

In the United States, commercial building designers of low-slope roofs have a choice of assemblies. These include the use of concrete decks or steel decks, and cementitious, gypsum-based or high-density foam cover boards. The aim of this study was to quantify the dynamic thermal properties of a range of possible assemblies using published thermophysical properties. These data were then used to model dynamic heat flow through the assemblies. The author hopes that such data will be used to improve the energy efficiency of commercial roofs and to provide the basis for experimental verification studies.

PREVIOUS STUDIES

Kossecka and Kosny[5] noted that prior research had found that specific distributions of mass and insulation inside the wall of a building provided for reduced heating and cooling loads. That research indicated that walls with the insulation on the outside always performed better than those with insulation on the inside. While the studies cited by Kossecka and Kosny were largely empirical, Kossecka and Kosny used whole-building modeling to examine the effects of multilayered walls with different dynamic thermal properties. Their modeling for six US climatic zones suggested that insulation on the outside of a wall and thermal mass on the inside would give improved thermal performance.

As noted by Verbeke[6] in an extensive recent review of the topic, increased thermal mass may offer additional energy savings, but some researchers have found the opposite to be true. Verbeke concluded that the wide range in apparent energy demand (between +300% and -80%) was the result of many factors. These included poor definition of thermal mass whereby researchers frequently used the relative terms “light,” “medium,” and “heavy” without quantification. Other factors influencing the range in apparent energy demand included variations among studies in terms of location, climate, building use, and the measure used—such as air conditioning or heat only—versus annual total energy cost.

For the effective use of thermal mass, it has been argued that activation is required whereby thermal energy is stored or extracted depending on demand. Activation would be accomplished using, for example, embedded hydronic pipe systems. In a review of the topic, Olsthoorn et al.[8] found that potential benefits of added thermal mass included improved thermal comfort for the occupants and the shifting and shaving of peak energy demand. While not noted specifically by Olsthoorn et al., the possible reduction in peak energy demand could reduce electric demand charges where such charges are in force.[10]

Much of the research cited by both Verbeke[6,7] and Olsthoorn et al. contains only qualitative descriptions of thermal mass and often does not discuss the impact of adding thermal mass to specific building elements such as the foundation, exterior walls, interior components, or roof. Also, research has included a mixture of building types such as residences and offices.

To examine the thermal performance of walls, Balaji et al.[11] modeled a range of wall configurations constructed of common building materials with well-defined thermophysical properties. They concluded that multilayered walls comprising materials with different dynamic properties could improve thermal performance. Their work could be used as a basis of wall design or for experimental verification.

DYNAMIC THERMAL PROPERTIES

In any roof assembly, the amount of thermal energy entering a building is reduced and delayed as shown in **Fig. 1**. The time lag Φ is calculated as follows:

$$\Phi = t_{T_{outside(max)}} - t_{T_{inside\ (max)}}$$

where $t_{T_{outside(max)}}$ and $t_{T_{inside\ (max)}}$ are the times of day, respectively, when the maximum outside and inside surface temperatures are reached. This time lag could be important for buildings that are occupied only during the day, such as offices. The time delay caused by a building’s enclosure could be why some offices become uncomfortably hot during late afternoon, as the heating, ventilating, and air-conditioning equipment (HVAC) system fails to compensate for the delayed heat flow into the interior space.

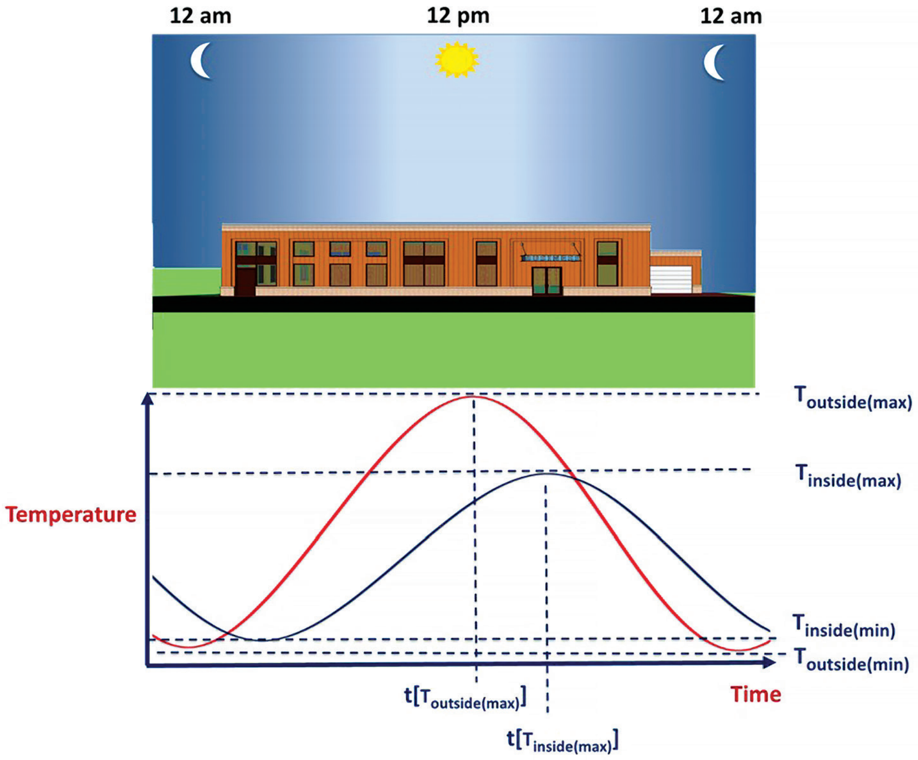

Figure 1. The diurnal temperature change of a roof assembly’s outside and inside surfaces, showing a reduction in temperature amplitude on the inside surface and a time delay.

The decrement factor DF is a measure of the reduction in amplitude of the heat flux entering the building enclosure from the outside and that reaching the inner surface. It is calculated as follows:

$$DF = \frac{T_{inside(max)} - T_{inside\ (min)}}{T_{outside(max)} - T_{outside\ (min)}}$$

Also, in any real-world situation, there is the dynamic effect of exterior temperature swings that lead to a periodic thermal transmittance. If the periodic thermal transmittance is low, the impact of outside thermal load will be reduced.

The time delay and decrement factor are results of certain fundamental material thermophysical properties. These in turn can be used to derive a set of thermophysical characteristics that quantify the dynamics of heat transfer.

FUNDAMENTAL THERMOPHYSICAL PROPERTIES

The three fundamental thermophysical properties of materials are thermal conductivity, density, and specific heat capacity.

Thermal Conductivity

Building design professionals are very familiar with thermal conductivity K measured as watts per meter per kelvin (W/[m•K]). It is normally used to characterize individual materials and is a measure of the heat flow through a material when a temperature gradient of 1 K (1°C) is applied. Thermal conductivity is measured when heat flow has equilibrated, and it does not include any time lag.

Density

Density ρ is a measure of the mass m per unit volume v:

$$\rho = m/v$$

While this is a straightforward measure for most materials, the density of building products such as polyisocyanurate (polyiso) insulation can be harder to define because of the facers used as well as a small density gradient within the foam.

Specific Heat Capacity

Specific heat capacity C_p is defined as the amount of heat required to raise the temperature of 1 kilogram of a substance by 1 kelvin. Thus, it is expressed in units of J/(kg•K).

At the onset of initiating a thermal gradient across a material, heat flow through that material is delayed by the material’s specific heat capacity. It takes energy to raise the material’s temperature, an action required before heat can then transmit.

DERIVED THERMOPHYSICAL PROPERTIES

As noted, the fundamental thermophysical properties are measured at equilibrium and do not include any time lag or delay. For that, the following derived properties need to be considered.

Thermal Diffusivity

Thermal diffusivity α is a measure of the rate at which heat propagates from one point to another point in a material. It is the rate of transfer of heat from a hot side to a cold side, expressed in units of m^2/s, and is calculated as follows:

$$\alpha = {}^{K}\!\big/\!(\rho \cdot C_p)$$

Heat moves rapidly through a substance with high thermal diffusivity because the substance conducts heat quickly relative to its volumetric heat capacity or "thermal bulk."

Thermal Inertia

Thermal inertia is the slowness with which the temperature of a material approaches that of its surroundings. It is a product of thermal conductivity, density, and specific heat capacity and is expressed in units of J^{-2}•K^{-1}•s$^{-½}$.

$$\text{Thermal inertia} = (K \cdot \rho \cdot C_p)^{½}$$

From a building enclosure perspective, thermal inertia could be considered as the rate at which the interior surface can supply heat into the interior, assuming a temperate climate. It is arguable that thermal inertia is not the best property to use to characterize a building enclosure component in terms of thermal lag (that is, the time delay for an exterior temperature change to affect the interior temperature).

Thermal Mass

It is often thought that thermal mass is essentially equivalent to gravimetric mass. Conceptually, this gives rise to the view that the more massive a construction is, the better its thermal mass will be. However, consider two blocks—one of steel and one of concrete, each having the same gravimetric mass. The two materials have different specific heat capacities and are not equivalent in terms of thermal properties. In addition, the thermal conductivity of steel is significantly higher than that of concrete.

Thermal mass is a property of a material that enables the material to store heat. It is the product of density ρ and specific heat capacity C_p and is expressed in units of J•m^{-3}•K^{-1}.

$$\text{Thermal mass} = \rho \cdot C_p$$

Importantly, thermal mass does not fully describe thermal lag. High thermal mass would change the decrement factor, dampening out heat transmission, but it is only indirectly linked to thermal delay.

Periodic Thermal Transmittance

Periodic thermal transmittance is defined as the complex amplitude of the density of heat flow rate through one surface of the component or assembly, divided by the complex amplitude of the temperature on that side when the temperature adjacent to the other side is held constant.[12]

The time lag and decrement factor can be calculated from a material's thermophysical properties, as described by Asan.[13]

LOW-SLOPE ROOF DESIGN

While local building codes and historical practices have led to some regional variations in low-slope roof design, most large low-slope roofs in the United States are based on steel or concrete decks. They generally consist of polyiso and a single-ply membrane such as thermoplastic polyolefin (TPO). (Note: Single-ply membranes represent more than 60% of the total low-slope roof area installed each year per interal GAF sales data for 2020.)

Figure 2 shows schematically the basic design elements of single-ply, low-slope roof assemblies constructed over steel and concrete decks. For each deck type, two approaches are indicated, the first representing a minimum design that could meet code requirements in many regions and the second representing enhanced designs offering improved impact resistance by virtue of a cover board immediately below the membrane.[14,15] Also, the second approach includes the use of a vapor retarder to reduce condensation risk.[16]

PHYSICAL PROPERTIES OF STUDY COMPONENTS

Table 1 lists the key physical properties for the common roof assembly layer materials used in this study and shown in Fig. 2.

METHODOLOGY

While thermal mass and thermal inertia calculations are straightforward for individual components, such calculations for multi-component building enclosure assemblies and the dynamic periodic thermal transmittance are more complex. Calculation of the effects of thermal mass has been described in ISO 13786,[12] which also provides directions for validating calculation methodology. For this study, a validated tool supplied by HTflux[17] was used to perform the calculations for the various roof assemblies.

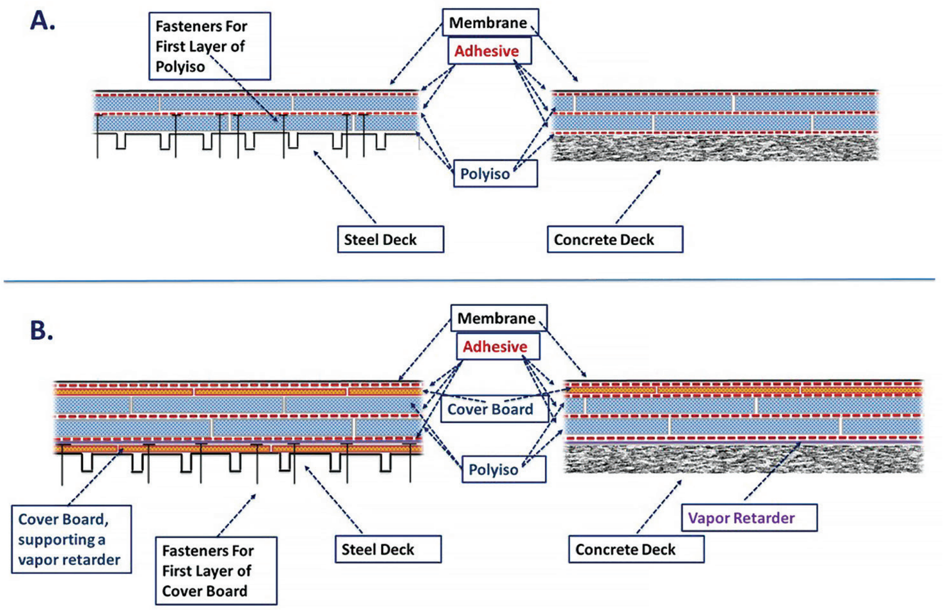

Figure 2. Schematics showing basic roof design of large commercial roofs. The two designs on the left are based on steel decks, whereas those on the right are over concrete decks. The upper designs, A, represent typical designs that would meet most minimum code requirements. The lower two designs, B, represent enhanced designs offering improved impact resistance and a lower risk of condensation.

	Thermal conductivity K (W/[m•K])	Density ρ (kg/m^3)	Specific heat capacity C_p (J/[kg•K])	Thermal mass × 10^{-6} ρ•C_p (J•m^{-3}•K^{-1})
60 mil (1.5 mm) TPO membrane	0.1199	1020	1200	1.224
Polyisocyanurate	0.0253	27	1500	0.041
High-density polyisocyanurate	0.0289	132	1585	0.209
Gypsum board	0.1288	769	1090	0.838
Concrete, structural lightweight	0.68	1623	834	1.354

Note: Properties represent typical product values, which are subject to manufacturing variances between suppliers and plants, and the like. TPO = thermoplastic polyolefin.

Table 1. Key physical properties for common low-slope roof assembly layer materials used in this study.

RESULTS

Four roof assemblies were analyzed for time delay, periodic thermal transmittance, and decrement factor.

- Assembly 1 is a well-insulated assembly often found over steel decks (*R*-value of approximately R-34).
- Assembly 2 is included for comparison, having no insulation above the structural lightweight concrete deck.
- Assembly 3 is combines polyiso insulation over a structural lightweight concrete deck.
- Assembly 4 represents an example of a high-performance roof assembly applied over a steel deck. The gypsum board could be used as a base for a vapor retarder. The high-density polyiso cover board would provide for improved impact resistance.

Note that the steel deck was not included in Assembly 1 or 4 due to its very high thermal conductivity and hence negligible effect on heat flux delay, along with its complex geometry and "porosity." Analysis of air exchange with the underside of steel decks and the effect of the fluted design was beyond the scope of this study.

Table 2 presents the dynamic thermal properties, time delay, periodic thermal transmittance, and decrement factor for each of the four assemblies.

Peak Temperature Time Delay

The time delay indicated in Table 2 is measured between the peak external temperature and the internal peak temperature. Assembly 1, based on polyiso over a steel deck, has a time delay of 1.64 hours. This potentially explains why the top floors of buildings become warmer during midafternoon periods in the summer. The external temperature will peak between noon and 1 p.m. when the sun is overhead. However, the heat flux into the building is delayed until 2 p.m. to 4 p.m.

Assembly 2, a structural lightweight concrete roof without insulation, is projected to delay the peak internal temperature by 4.24 hours. However, a combination of lightweight structural concrete deck with polyiso, as represented by Assembly 3, delays that peak temperature by more than eight hours. This would mean that, for an office building, the peak heat flux into the building could be delayed until after normal working hours.

Assembly 4, a high-performance roof assembly over a steel deck, delays the peak temperature by 2.60 hours. Such an assembly is optimized for impact resistance and includes a gypsum board as a substrate for a vapor retarder. This time delay would result in the peak heat

Assembly	Layer name (bottom to top)	Layer thickness (m)	Layer thickness (imperial)	Time delay, hours	Periodic thermal transmittance, W/m²K	Decrement factor
1	Polyisocyanurate	0.1500	5.91 in.	1.64	0.161	0.965
	TPO membrane	0.0014	60 mil			
2	Structural lightweight concrete	0.1500	5.91 in.	4.24	1.798	0.723
	TPO membrane	0.0014	60 mil			
3	Structural lightweight concrete	0.1500	5.91 in.	8.09	0.048	0.296
	Polyisocyanurate	0.1500	5.91 in.			
	TPO membrane	0.0014	60 mil			
4	Gypsum cover board	0.0127	0.5 in.	2.60	0.144	0.938
	Polyisocyanurate	0.1500	5.91 in.			
	High-density polyisocyanurate	0.0127	0.5 in.			
	TPO membrane	0.0014	60 mil			

Note: The steel deck was not included in Assembly 1 or 4 due to its very high thermal conductivity and hence negligible effect on heat flux delay, along with its complex geometry and "porosity." TPO = thermoplastic polyolefin.

Table 2. Dynamic thermal performance of four roof assemblies.

flux into the building during working hours for a building occupied only during the day.

Periodic Thermal Transmittance

Assembly 3, consisting of a structural lightweight concrete deck, polyiso, and TPO membrane, had the lowest periodic thermal transmittance of 0.048 W/m^{2}K. This not only means that Assembly 3 had a large time delay in peak heat flux but also that the amount of energy entering the building through the roof would be low. The polyiso insulation resists the heat flux, and the lightweight structural concrete has a high density so that it absorbs what heat does come through the polyiso, thereby delaying the impact of the heat flux on the building interior. This assembly would significantly dampen the effect of exterior temperature swings and increase occupant comfort.

For buildings such as offices or schools, and any other building occupied only during the daytime, the combination of high thermal resistance and large thermal mass could be a significant advantage. The combination of a large time delay and low periodic thermal transmittance for Assembly 3 would lower the thermal demand on air-conditioning units and potentially also reduce temperature swings within the building. This could improve comfort for occupants and reduce HVAC cycling.

Decrement Factor

The decrement factor, or reduction in the heat flux amplitude entering a building interior versus the external amplitude, is lowest for Assembly 3. This finding further supports the argument that a combination of insulation, as provided by polyiso, and thermal mass, as provided by the structural lightweight concrete, could lead to the best interior thermal comfort among the four assemblies modeled here.

CONCLUSION

Based on findings from this study, the following points are notable:

- The thermal property data shown here could be used in modeling exercises to better understand how to design and optimize energy-efficient buildings. For the four roof assemblies, the data showed a range of less than two to more than eight hours' delay in peak thermal transmittance. The magnitude of this delay could significantly affect energy use in buildings occupied during the day.
- Clearly, structural lightweight concrete has a far higher thermal mass than other materials commonly used in roof assemblies.
- Among the four assemblies modeled here, a combination of thermal insulation and thermal mass seems to offer the best opportunity for improved thermal comfort and energy efficiency for buildings occupied during the daytime. However, assemblies that simply delay thermal transmittance until later in the diurnal cycle may not provide as much improved energy efficiency on a 24-hour basis (that is, for buildings with continuous occupancy).
- Conventional roof assembly design typically considers thermal resistance only. However, for further improvements in energy efficiency, it could be worthwhile to consider thermal mass, particularly for buildings occupied only during the daytime.

While this study suggests that including thermal mass into a building enclosure could bring benefits, it should be noted that other factors were not taken into account in this investigation. These include real-world weather conditions, occupants' interactions, and a building's overall geometry. Energy savings are not guaranteed, and the amount of savings may vary based on climate zone, utility rates, radiative properties of roofing products, insulation levels, HVAC equipment efficiency, and other factors.

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