Revival

TECHNICALMONOGRAPH 1

Phase change materials in buildings – Virtual thermal mass

This technical monograph is one of a set produced as part of the 'REVIVAL' project – an EU Energie Programme supported demonstration project of energy efficient and sustainable refurbishment of non-domestic buildings in Europe. The monographs explore some of the main energy and comfort issues which arose during the Design Forums held with each of the six sites. The four monographs are entitled:

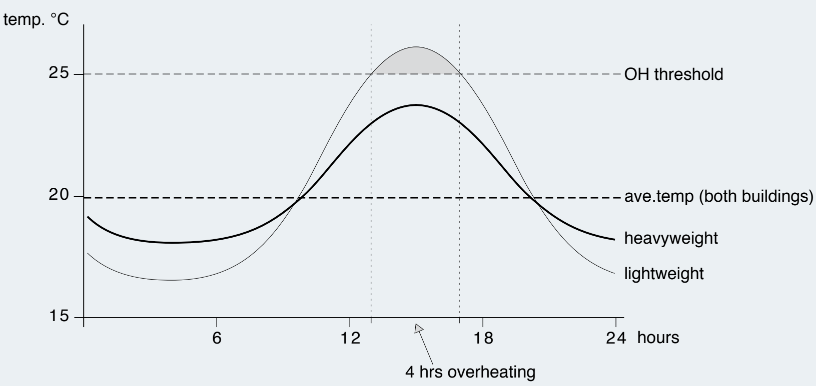
- **Thermal mass and phase change materials in buildings**
- Adaptive thermal comfort standards and controls
- Natural ventilation strategies for refurbishment projects
- High performance daylighting

Energy efficient refurbishment must consider the thermal performance of the existing building and how it may be changed for the better (or worse) by the intervention. Phase change materials (PCM) offer a possibility for improving the thermal response of the building by changing the effective thermal mass.

What is thermal mass?

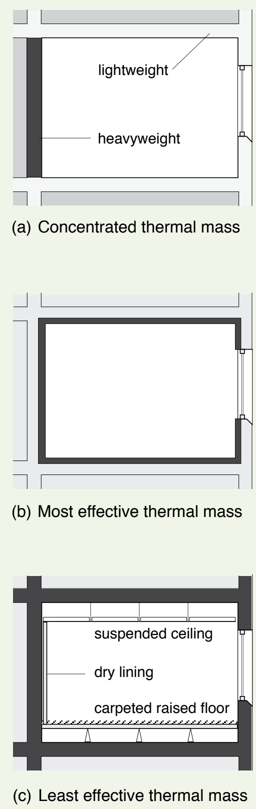
It is the part of the building which stores and releases significant quantities of heat during a typical daily cycle. It is important because it can increase the usefulness of solar gains and internal gains, and reduce the risk of overheating (Figure 1).

▼ Figure 1
The temperature in a lightweight building (low thermal mass) rises above the overheating threshold, whereas that in the heavyweight building does not, although the average daily temperature is the same and no solar gains are available.

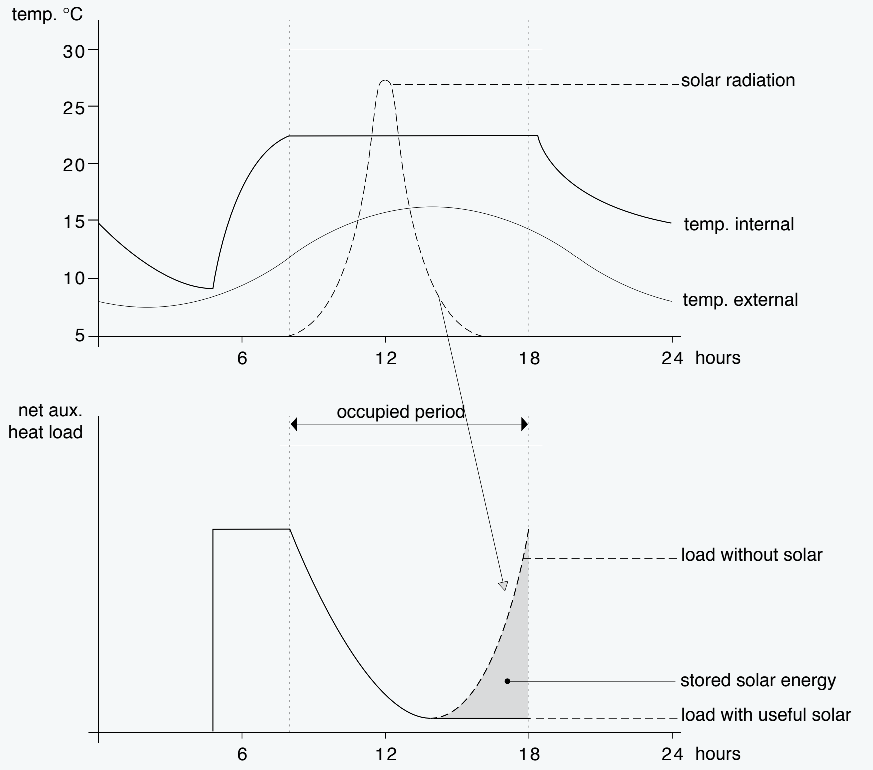


Dense materials have more effect than lightweight materials in providing thermal mass, but it is essential that the mass is accessible from the occupied space and/or the space in which the gains are made (Figure 2).

▼ Figure 2
Thermal mass must be thermally coupled to the occupied space. It must also have the maximum surface area possible. Thermal mass can be coupled remotely by a mechanically driven air flow.



▶ Figure 3
Surplus solar gains made at midday are stored in the mass, and become available to offset the heat load later in the day when the outside temperature drops and there is a net heat load.



How does it help us?

Winter sunshine may bring ½ kW into the room for every m² of south-facing glazing. This may be much greater than the current heating load for the room and in a room with no capacity to store heat, would lead to overheating, and/or the rejection of the heat by opening the window or running the A/C plant. A room with accessible thermal mass would heat up much more slowly because more heat would be absorbed by the mass. When the sun is no longer present and the temperature of the room drops, this heat will be released into the room, delaying the need for auxiliary heating (Figure 3). Thus, thermal mass is normally regarded as an essential constituent of, *solar architecture*.

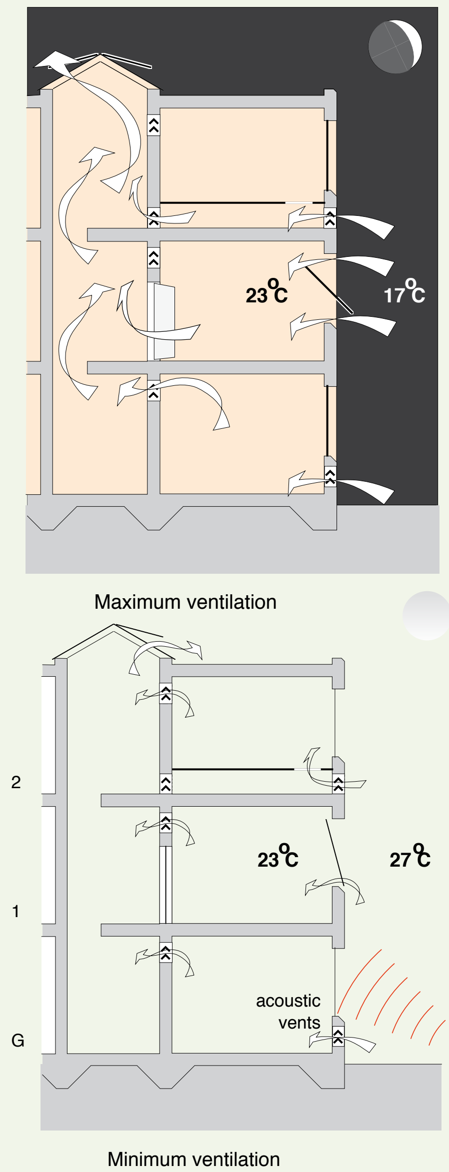
In summer, the effect is similar, except that the stored heat is probably not required at all, and is taken out of the mass by ventilating the building when the air temperature is lowest, usually at night (Figure 4). The beneficial effect is that it reduces peak daytime temperatures by a much as 3-5 °K.

The physics of thermal mass

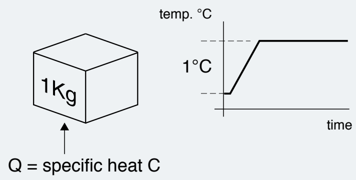
Thermal mass can be quantified. It is the product of the mass (in kg) and the Specific Heat (in Joules/kg °C). The Specific Heat is the heat required to raise the temperature of one kg of the material by one °C (Figure 5). It follows that the units of thermal mass are Joules/°C.

Thermal mass is only effective in storing heat if the heat can flow into it. The deeper into the material, the less heat flows into it (in a given time) and so the less impact it has (Figure 6). The result is that for diurnal (24 hour) temperature cycles, for thermally massive materials such as masonry or concrete, only the first 50mm has much effect. For longer cycles – e.g. a sequence of hot days (or heat wave), deeper thermal mass will slow down the gradual heating up of the building. Only very

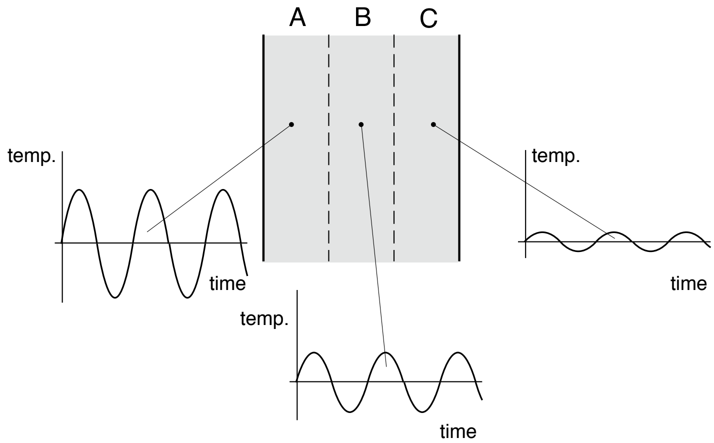
▶ Figure 4
Thermal mass which absorbs unwanted gains in the daytime, has to be 'emptied' of stored heat to be ready to absorb the gains the next day. This is most effectively achieved by high rates of ventilation at night, when the air is coolest.



▼ Figure 5
The definition of Specific Heat. The quantity of heat required to raise the temperature of one kilogram of the material by one degree Centigrade.



▶ **Figure 6**
When a surface is subjected to a temperature swing heat flows into the mass in the form of a wave whose amplitude diminishes with depth. This means that the deeper the mass, the less heat is stored (per unit volume) for a given temperature swing at the surface, i.e. layer C stores much less heat than layer A.



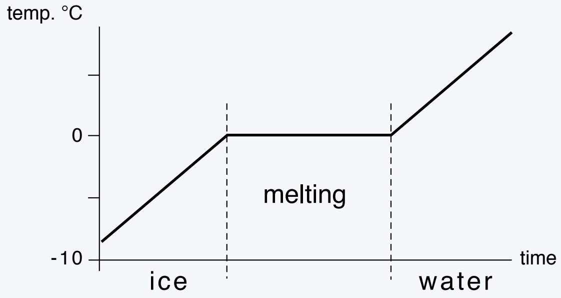
deep mass, e.g. that which might be found in buildings such as cathedrals and castles, will have a significant effect on a seasonal level – i.e. mean monthly temperatures inside will lag behind the mean monthly temperatures outside. These effects are described as *thermal inertia*.

Good news and bad news about thermal mass

Whilst thermal mass has the benefit of reducing swings in temperature which could lead to overheating, and of increasing the benefit of solar gains in winter, it carries some penalties.

In intermittently occupied buildings (e.g. a primary school) a heavyweight building will require more pre-heating than a lightweight building. Since a large proportion of the heating energy is used at this time, when there are no useful internal gains present, the difference can be quite significant. This is illustrated in Figure 7.

In providing thermal mass that is coupled to the occupied space the acoustics may have to be compromised. Thermally massive surfaces are usually hard and dense, and the resulting acoustic will be noisy and reverberant. In practice, typical office buildings for example, have carpeted floors and suspended ceilings, providing a good acoustic environment, but very poor coupling to the thermal mass in the structure.



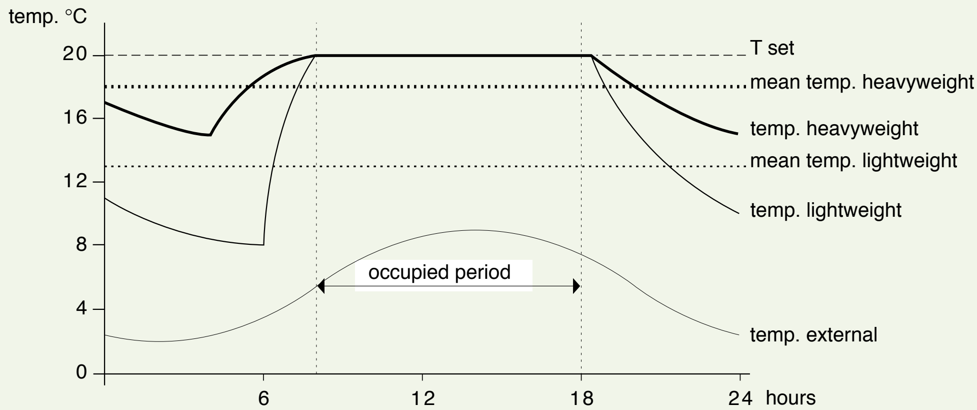
What is a phase change material?

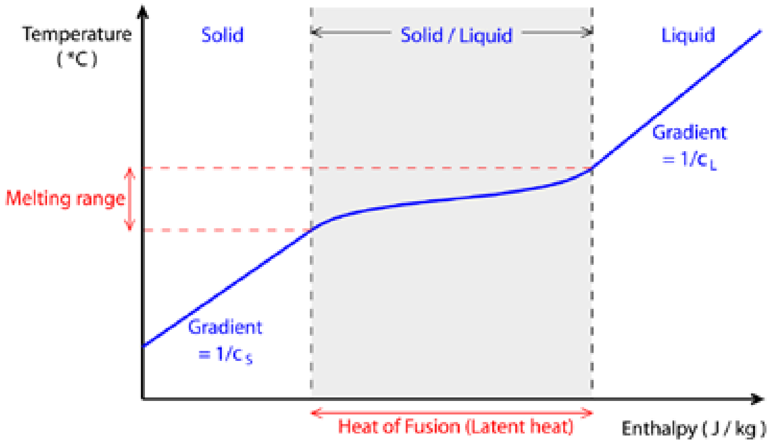
The *change of phase* of a material means it changes from a solid to a liquid or from a liquid to a gas. Due to the re-arrangement of the molecules, it involves a considerable amount of energy. We are aware of this when we feel the cooling effect of wetness on the skin, or use a small piece of ice to cool down a drink.

Figure 8 tells this story very well. A fixed mass of water (initially ice) is steadily heated up from

▲ **Figure 8**
This graph demonstrates the thermal effect of phase change. It shows the temperature of a fixed mass of water, initially at –10°C, as it receives a steady input of heat. Note that as soon as phase change commences (melting) heat is absorbed without raising the temperature. The amount of heat required for melting is roughly equivalent to raising the temperature of the same mass 144°K.

▶ **Figure 7**
Heat loss from the building is proportional to the difference between the inside and outside temperature, integrated over the day. This is the area between the temperature curves for the buildings and the external temperature curve. It is larger for the heavyweight building than the lightweight building.





-10°C. Up to 0°C, the ice behaves like normal thermal mass, increasing its temperature as it absorbs heat at a rate of 4.2 kJ/kg °C. As it reaches 0°C it begins to melt. This process absorbs large amounts of heat without increasing in temperature. In fact it absorbs 322 kJ/kg. When all the ice is melted, i.e. the change of phase is complete, the temperature continues to rise. The heat that causes a change in temperature is often referred to as *sensible heat*, because it is sensed by a temperature rise, whilst the heat that changes phase is referred to as *latent heat*.

Now consider the effect of using a material that melted at 24°C instead of 0°C placed on the surface of room in contact with the air. As the room temperature increased above 24°C, heat would flow into the PCM causing it to melt, instead of causing the air to heat up further. If there were sufficient PCM to continue to melt until the peak heat input was past, overheating would have been prevented. It must be pointed out, however, that the room will now cool down more slowly, since as the PCM solidifies, the latent heat absorbed in the melting process will be returned to the room.

In practice, the phase change takes place over a range of temperatures as in Figure 9 (Figure 8 is a theoretical curve). This is partly due to the need for temperature gradients in the PCM in order for the heat to flow, and partly due to the physical chemistry of the materials used.

We can see then that the PCM is behaving as thermal mass, but because of the large amount of heat involved, it is very “concentrated”. For example a 10mm layer of PCM material has the effect of about 50mm of concrete. However, it must not be forgotten that the heat absorbing process of normal mass takes place over all ranges of temperature, whereas the PCM is only effective at a specific temperature range.

What are the actual materials used?

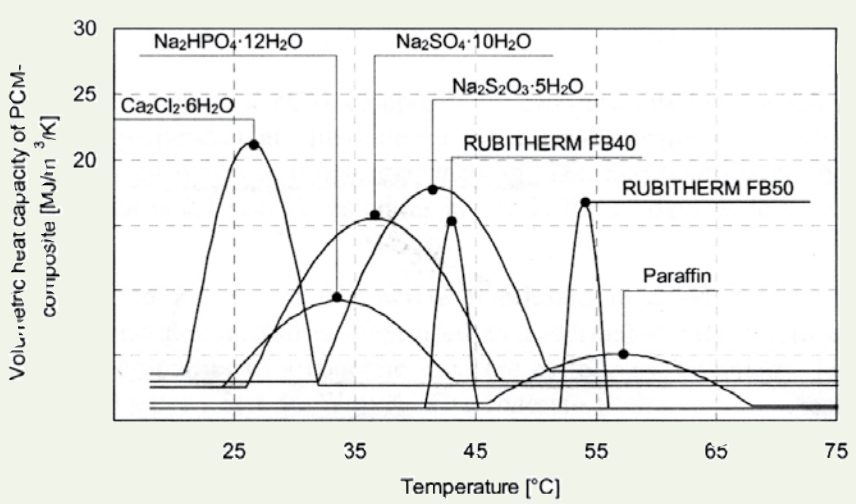
There are two classes of materials – waxes and salts. Waxes are chains of polymer molecules (paraffins) and solidify into a crystalline form. The salts are used as a saturated solution in water – solidification involves the water molecules and the salt ions making a crystalline structure. The commonest salt used is Sodium Sulphate ($Na_2SO_4.10H_2O$) or Glaubers salt, but additives are put in to tailor the melting point temperature to the exact requirement of the application.

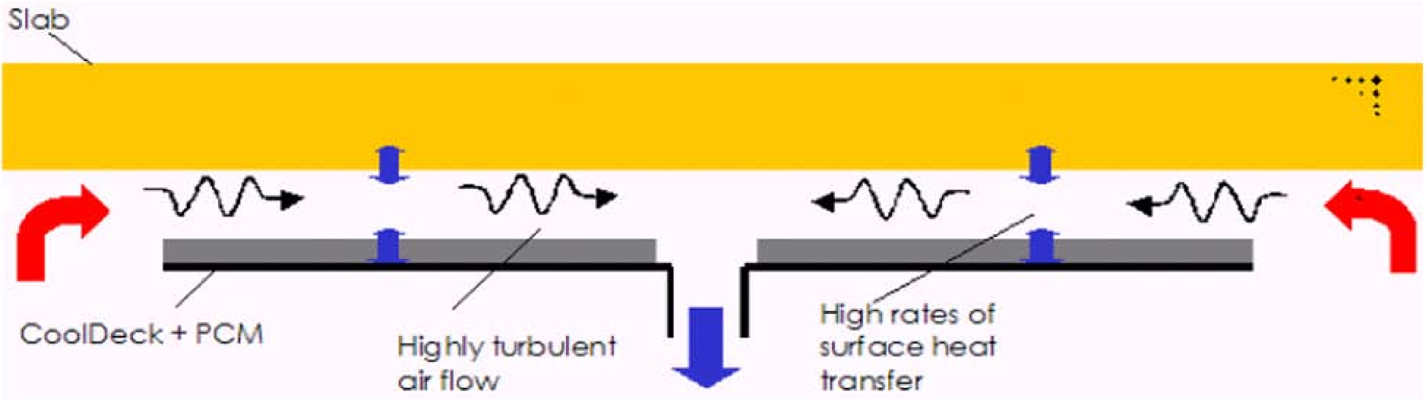
Good news and bad news about PCM

As we have seen, small amounts of PCM have the effect of large amounts of normal mass. Thus, in a lightweight interior such as our office example (carpeted floor, suspended ceiling), in principle, sachets of the PCM material could be laid on metal trays in the ceiling, converting the interior to “thermally massive”. Furthermore, the transition temperature for overheating prevention, would be chosen to be somewhere

▲ **Figure 9**
Realistic melting curve for PCM showing melting temperature range. Enthalpy is the total heat energy; sensible + latent and is equivalent to the time axis in Figure 8

▼ **Figure 10**
Materials used in PCM applications. This graph is presented differently from the melting curves and shows the effective heat capacity (thermal mass) as a function of temperature. The temperature range under the curved part of the graph is the melting range.





▲ Figure 11
The "COOLDECK" system as used at the REVIVAL project in Stevenage. The remote phase change thermal store is coupled to the occupied space by ducted air drawn in from the room via a grille in the suspended ceiling. The air is also brought in contact with the conventional mass of the slab.

1 By natural convection or radiative exchange between the PCM and the room and contents.

▼ Figure 12
Metal trays containing PCM attached to underside of concrete slab, coupled with room air by forced convection in COOLDECK system used at Stevenage

in the mid 20°s and thus would not carry the disadvantage of conventional thermal mass during the warm-up period.

The bad news is that PCM is mono-functional and an extra cost, whereas conventional thermal mass – a masonry wall or a concrete floor slab – is already serving an enclosing and/or structural function. Secondly, most PCM materials have a finite lifetime in terms of cycles – some kind of degradation of the material takes place. Thirdly, in spite of the large heat capacity at the melting temperature, due to the relatively poor thermal conductivity of the material, large surface areas must be available to passively[1] couple the material with the space; this may compromise acoustic performance and present other practical difficulties.

The latter problem has prompted designers to adopt hybrid systems involving fan driven airflow to couple the PCM heat sink to the occupied room in the daytime, and to the cool night air at night. This approach carries extra costs, but when compared with conventional A/C, for capital and running costs, is very favourable. It also allows stricter control. This principle is adopted in the REVIVAL project for Stevenage Council offices in the UK, (Figures 11–13).

PCM application design configurations.

The way that the PCM is coupled to the occupied space, i.e. the way that it can absorb and liberate heat to the space, is a critical part of the application.

PCM is available in several different forms but the commonest is in sealed plastic sachets (Figure 13) which are used in conjunction with a support system such as metal trays or ceiling tiles. PCM is also available incorporated into wall coverings – "PCM wallpaper" and plasters. A third approach is to locate the PCM remotely in a "thermal accumulator" (Figure 14), coupling the space via mechanically driven air or water.

▼ Figure 13
PCM materials in sachets as used in Cooldeck system at Stevenage

▶ **Figure 14**
PCM thermal store at the Bristol Science Centre, by Chris Wilkinson Architects and Arup.

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Summary conclusions

PCM offers a way of increasing the effective thermal mass of a building, requiring less space than the equivalent 'conventional' mass. Since it can be retro-installed it has special value in refurbishment projects.

PCM installations can be made more effective by mechanically coupling the material with the space via fan-driven airflow; this also allows closer control which improves system efficiency. The Coefficient of Performance[2] of such a system at Stevenage is claimed to be 11:1 compared to about 3:1 for a typical A/C system.

Due to large surface area requirements, it is inherently a 'low capacity' system when used passively. As with all passive and hybrid systems 'prevention is better than cure'. In other words minimise the cooling loads by appropriate shading and internal gains reduction before specifying the PCM system.

In its heat storage role, PCM offers a way to reduce global energy consumption, only if it is used in conjunction with ambient heat sources or sinks – e.g. solar energy or the cool night air. Ice storage used in A/C systems, or PCM used in off-peak heat storage systems only delay the demand for conventional energy to a period when it is cheaper; it does not reduce the total energy use.

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Acknowledgements

I am grateful to Andrew Macintosh for the use of Figures 9, 10, 11, and 14.

2 The ratio of heat displaced by the system to the electrical power to drive it