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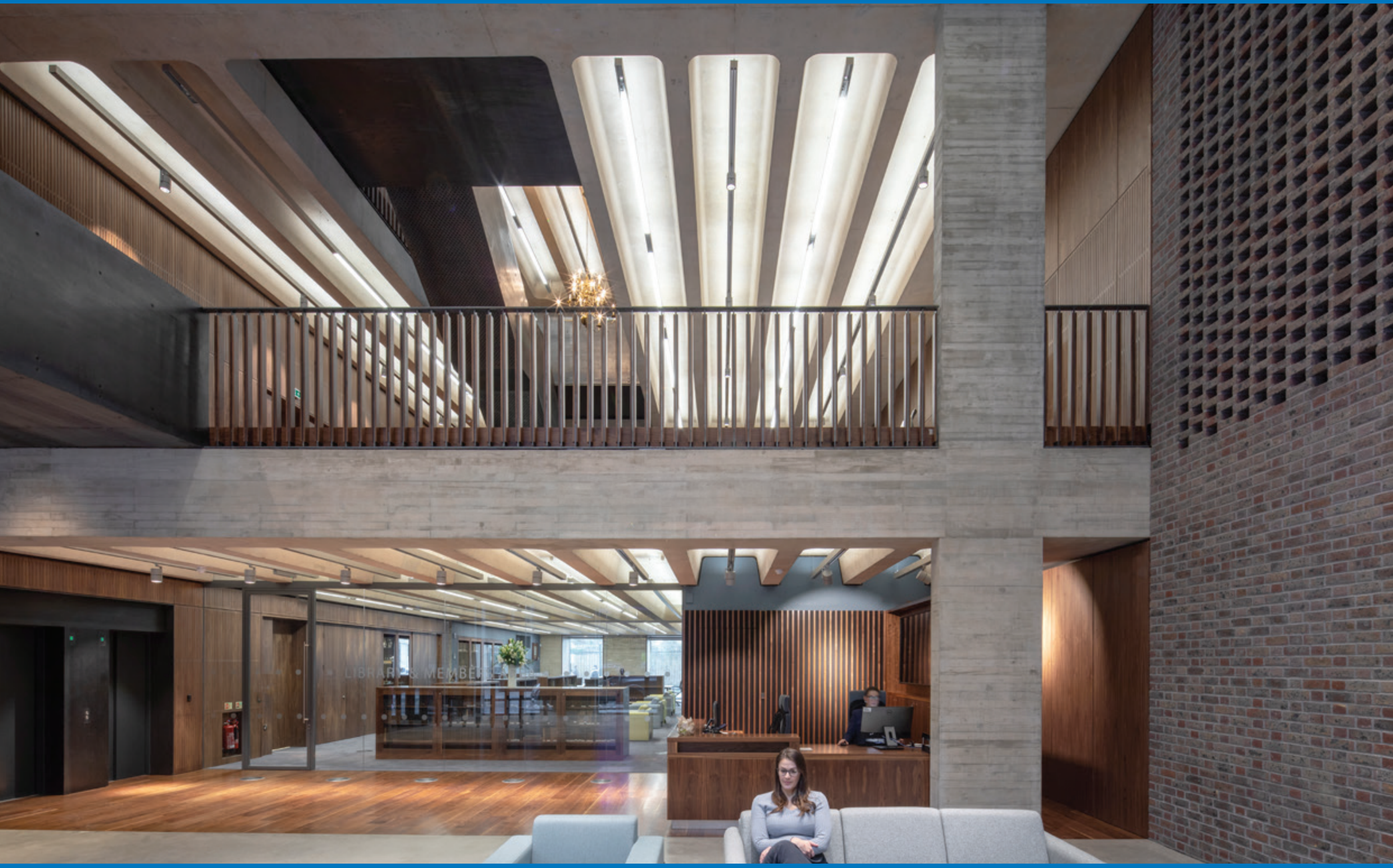
The Concrete Centre

Thermal Mass Explained



Thermal mass: what it is, how it is used and how it is measured

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Glossary of terms

Admittance
The admittance of a material is its ability to exchange heat with the environment when subjected to cyclic variations in temperature (see page 14). In practical terms, admittance values show the extent to which a specific floor or wall construction can absorb and release heat inside a building, typically over a 24 hour period.

Decrement delay
The time lag, measured in hours, for heat to pass through a material or construction element (see page 17). In practical terms, it is the delay between the peak outer and inner surface temperature of a wall or roof typically on a summer day as external heat gains pass through in a wave-like motion.

Decrement factor
This is the ratio between the cyclic temperature variation on the inside surface of a wall or roof compared to the outside surface (see page 17). In practical terms, it basically describes the stability of the inside surface temperature, typically over the course of a summer day.

Diurnal temperature variation
The daily temperature shift that occurs from daytime to night-time.

Diurnal heat flow
The heat that flows to and from a building or space over the course of 24 hours.

Mass enhanced U-value
This describes the ability, in certain climates, for heavyweight construction elements, to achieve better energy performance than suggested by their standard (steady-state) U-value.

k-value
k-value is short for Kappa value. It is a measure of thermal capacity used in SAP and SBEM (the compliance tools for Part L of the Building Regulations). The units are kJ/m^{2}K (see page 15).

Passive solar design (PSD)
PSD basically optimises a building's form, fabric and orientation to maximise solar gain from autumn to spring, whilst minimising it during the warmer part of the summer. At the same time, daylighting is maximised at all times.

Thermal mass
A concept in building design that describes how the mass of the building provides "inertia" against temperature fluctuations.

Cover image: The Royal College of Pathologists HQ in London features a concrete coffered ceiling which both minimises weight and makes full use of the concrete's thermal mass by maximising the surface area in contact with air. Architect: Bennetts Associates; Structural Engineer: Waterman Group. Image © Peter Cook.

Introduction

The energy used for space heating accounts for around 20 to 50 per cent of a building's energy consumption depending on type [1], and around 37% of the carbon emissions from all UK buildings [2].

In offices and similar building types, the use of thermal mass was, until recently, largely ignored in favour of an entirely air conditioned approach to cooling. However, with increasing energy costs and concern over CO_2 emissions, its ability to provide passive cooling is being rediscovered and applied in both new and refurbished buildings.

With the advent of a warming climate and a tendency for modern, highly insulated homes to overheat more easily, summertime performance remains a key driver for utilising thermal mass. This is typically provided by concrete and masonry which, in combination with effective ventilation, helps maintain comfortable conditions and reduce the risk of overheating. Conversely, this risk is likely to be increased by the lack of thermal mass in emerging lightweight factory-produced homes.

To lessen carbon emissions, revisions to Part L of the Building Regulations, along with the introduction of other codes and standards, have done much to reduce fabric heat loss through requirements for greater levels of insulation and reduced air leakage. These are very effective and well understood measures. Something less well known is that reducing heat loss from a building also enhances the passive performance of thermal mass. This is accounted for in the Standard Assessment Procedure (SAP) for Part L1 of the Building Regulations for new dwellings, which takes some account of thermal mass in the calculation of year-round building performance.

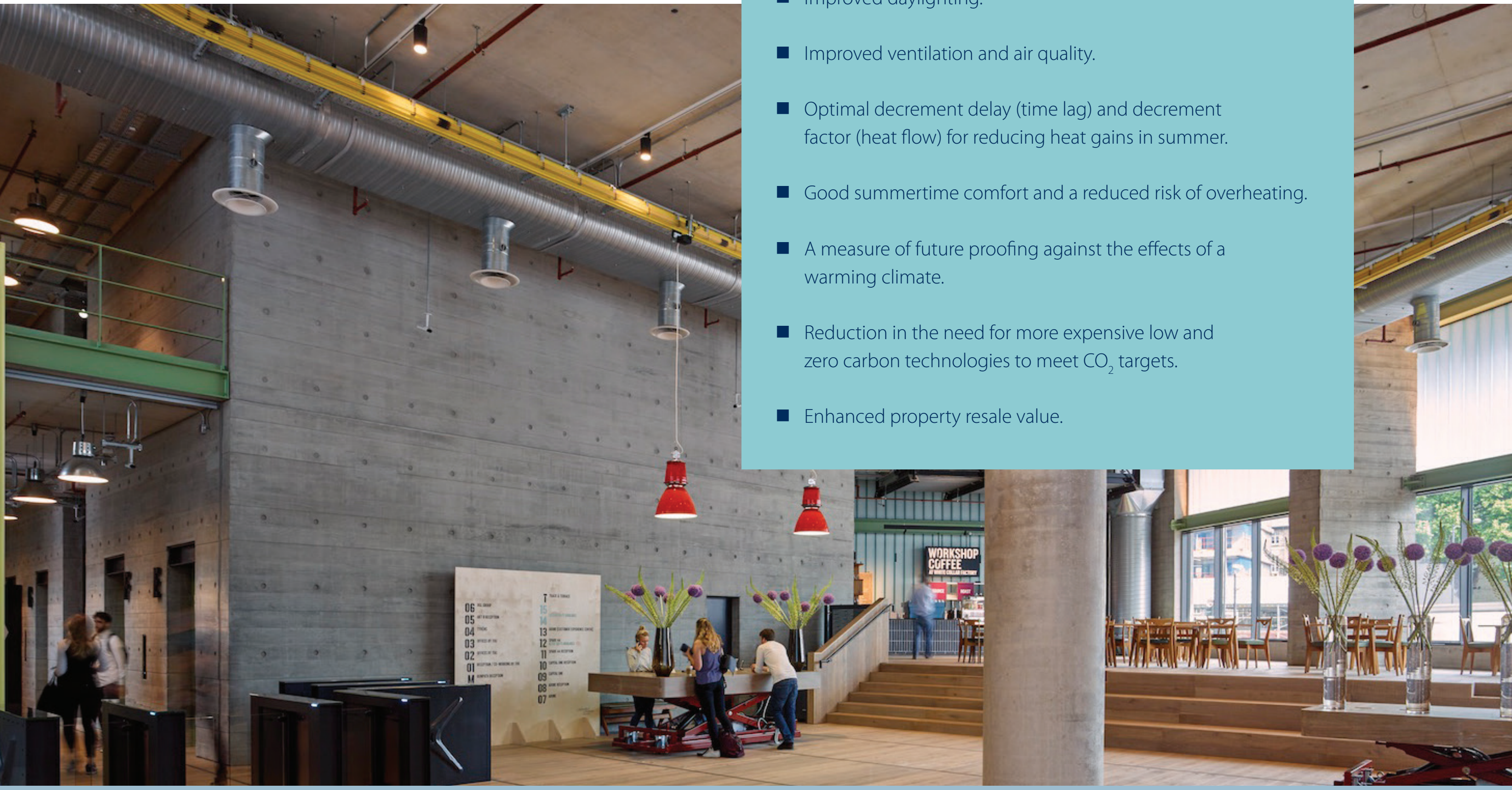
Whatever the building type, the use of thermal mass, requires a basic working knowledge of its function and how best to use it. That is the purpose of this short guide, which we hope you find useful.

Further guidance on thermal mass is available from The Concrete Centre – **www.concretecentre.com/thermalmass.**

Benefits of designing with thermal mass

Exploiting thermal mass on a year-round basis is not difficult, but does require consideration at the outset of the design process when requirements for the building form, orientation, fabric and finishes are being established. Providing this is done sympathetically, a more passive approach to design can realise benefits which include:

- Enhanced fabric energy efficiency and carbon savings over the life of the building.
- Improved daylighting.
- Improved ventilation and air quality.
- Optimal decrement delay (time lag) and decrement factor (heat flow) for reducing heat gains in summer.
- Good summertime comfort and a reduced risk of overheating.
- A measure of future proofing against the effects of a warming climate.
- Reduction in the need for more expensive low and zero carbon technologies to meet CO_2 targets.
- Enhanced property resale value.



White Collar Factory, London achieved an 'Outstanding' BREEAM rating. This striking office building used exposed concrete to achieve the maximum thermal mass benefit. Architect: AHMM; Structural Engineer: AKT II. Image © Timothy Soar.

What is thermal mass?

Thermal mass describes the ability of certain building materials to absorb heat, providing inertia against temperature fluctuations (see Figure 1).

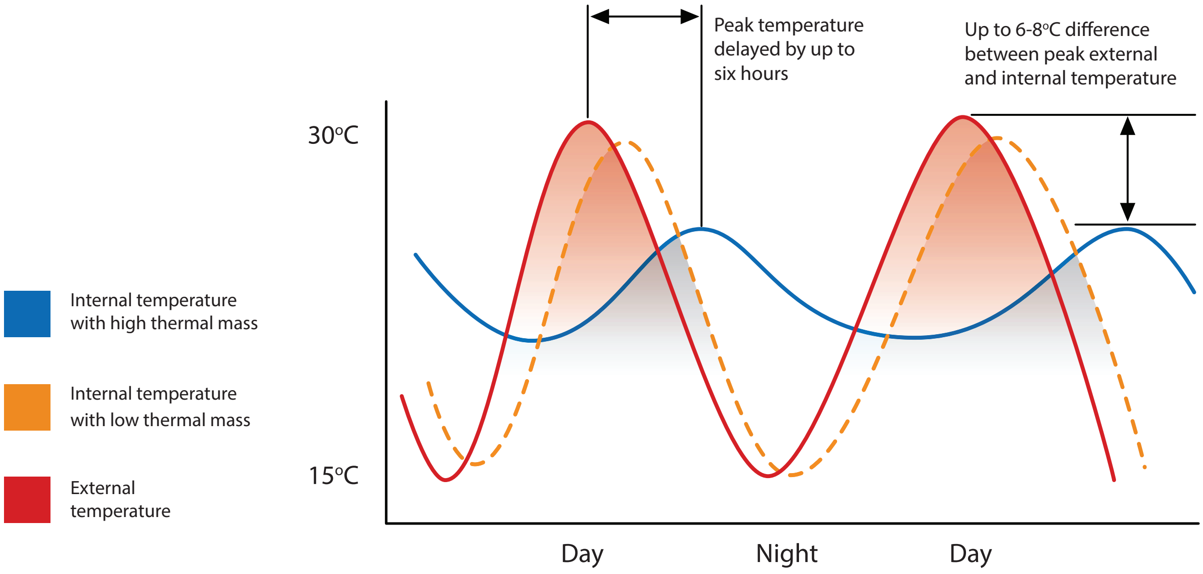
For a material to provide a useful level of thermal mass, a combination of three basic properties is required:

1. A high specific heat capacity; so the heat squeezed into every kilogramme is maximised.
2. A high density; the heavier the material, the more heat it can store.
3. Moderate thermal conductivity – so the rate heat flows in and out of the material is roughly in step with the daily heating and cooling cycle of the building.

Heavyweight construction materials such as brick, stone and concrete all have these properties (see Table 1). They combine a high storage capacity with moderate thermal conductivity (a combination of all the properties required). This means that heat moves between the material's surface and its interior at a rate that matches the daily heating and cooling cycle of buildings. Some materials, like wood, have a high heat capacity, but their thermal conductivity is relatively low, limiting the rate at which heat is absorbed during the day and released at night, although this can be useful in other ways (see page 17). Steel can also store heat, but in contrast to wood, it possesses a very high rate of thermal conductivity, which means heat is absorbed and released too rapidly to be synchronised with a building's natural heat flow.

Some materials, like timber, have a high heat capacity, but their thermal conductivity is relatively low.

Figure 1: Stabilising effect of thermal mass on internal temperature.



On warm summer days, walls and floors with thermal mass will steadily absorb heat at their surface, conducting it inwardly, and storing it until exposed to cooler air of the evening/night. At this point, heat will begin to migrate back to the surface and is released. In this way, heat moves in a wave-like motion alternately being absorbed and released in response to the change in day and night-time conditions.

The ability to absorb and release heat in this way enables buildings with thermal mass to respond naturally to changing conditions, helping stabilise the internal temperature and provide a largely self-regulating environment. When used appropriately, this stabilising effect helps prevent overheating problems during the summer and reduces the need for mechanical cooling. Similarly, the ability to absorb heat can help reduce fuel usage during the heating season by capturing and later releasing solar gains and heat from internal appliances (see pages 8-11). The seasonal use of thermal mass is explained in the next section.

The Simon Sainsbury Centre at Judge Business School, Cambridge uses an innovative natural ventilation system, in combination with the thermal mass, to minimise energy consumption. Architect: Stanton Williams; Structural Engineer: AKT II. Image © Hufton and Crow.

Table 1: Thermal properties of common construction materials.

Building material [3]	Specific heat capacity (J/kg.K)	Density (kg/m3)	Thermal conductivity (W/m.K)	Effective thermal mass
Timber	1600	500	0.13	Low
Steel	450	7800	50.0	Low
Lightweight aggregate block	1000	1400	0.57	Medium-high
Precast and in-situ concrete	1000	2300	1.75	High
Brick	1000	1750	0.77	High
Sandstone	1000	2300	1.8	High

Thermal mass in summer – how it works

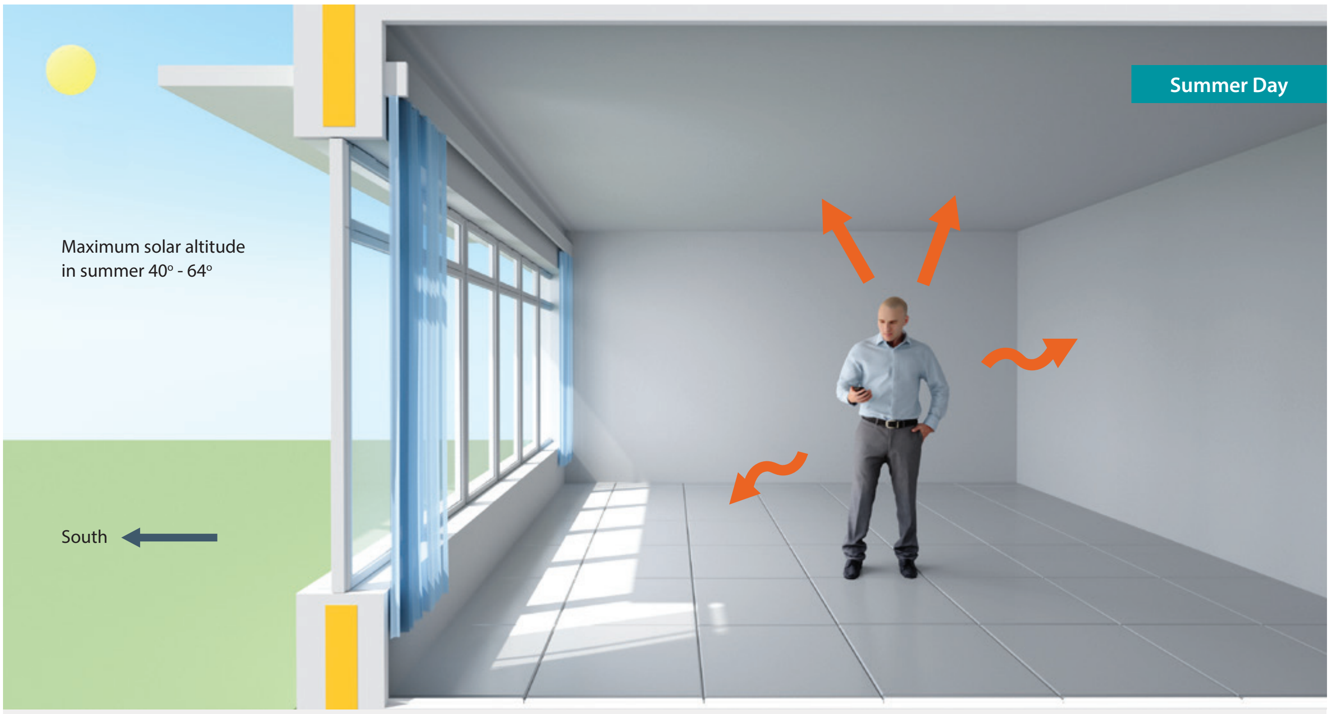
The benefit of thermal mass in residential buildings is well understood in warmer parts of Europe, but has become increasingly relevant in the UK, where hotter summers and highly insulated homes is leading to more frequent overheating problems. Its application in commercial buildings has also grown due to its ability to significantly reduce the cost and carbon associated with providing cooling.

During warm weather, much of the heat gain in heavyweight buildings is absorbed by the thermal mass in the floors and walls, helping prevent an excessive temperature rise and reducing the risk of overheating. This makes naturally ventilated buildings more comfortable and, in air-conditioned buildings with thermal mass, the peak cooling load can be reduced and delayed. The building fabric allows a significant amount of heat to be absorbed with only a small increase in the surface temperature. This is an important quality of heavyweight construction as the relatively low surface temperature results in a beneficial radiant cooling effect for the occupants, allowing a slightly higher air temperature to be tolerated than would otherwise be possible.

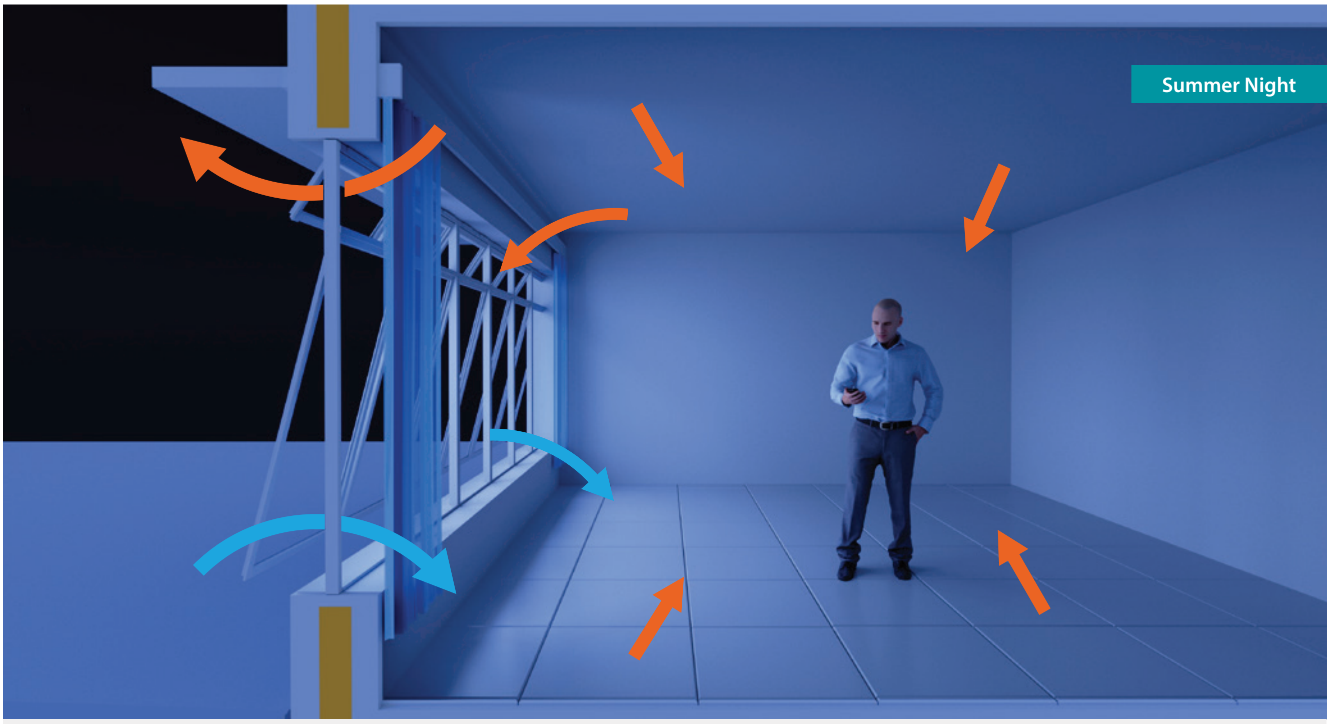
By allowing cool night-air to ventilate the building, heat that has built up in the fabric during the day is removed. This daily heating and cooling cycle works relatively well in the UK as the air temperature at night is typically around 10 degrees less than the peak daytime temperature, so it is an effective medium for drawing heat out of the fabric. This diurnal temperature variation is rarely less than 5 degrees, making night cooling reasonably dependable in the UK **[4]**. As the climate warms over the 21st century the diurnal variation is predicted to stay the same or increase slightly **[5]**, however the temperature range in which it occurs will progressively shift upwards. So, towards the end of the century, the effectiveness of night cooling is likely to diminish slightly as average temperatures increase. Despite this, the combination of thermal mass and night cooling is, and will continue to be, a useful means of helping buildings adapt to the effects of a warming climate **[6, 7, 8, 9]**.

The combination of thermal mass and night cooling is an effective means of helping buildings to adapt to a changing climate.

Figure 2: Thermal mass in summer.



- During very hot weather, windows are kept shut to keep out the warm air.
- Overhangs on the south elevation keep out the high angle sun during the hottest part of the day. Alternative forms of shading can also be used.
- Radiant and convective cooling is provided by thermal mass in the floor and walls, which absorb heat and help stabilise the internal temperature.
- Thermal mass helps ensure that surface temperatures remain relatively low, allowing building occupants to radiate body heat.



- Windows are opened at night to ventilate the building and cool the fabric.
- If another hot day is expected, the windows are closed again in the morning and the cycle is repeated.

Thermal mass in winter – how it works

The combination of tougher performance requirements and rising fuel costs, mean that we should make the most of passive techniques to heat our homes and places of work where practicable. This requires a whole-building approach to design, in which the orientation, glazing and thermal mass work together to help provide comfortable, low energy solutions.

A benefit of thermal mass that is perhaps less well known in the UK, is its ability to help reduce fuel consumption during the heating season when used in passive solar design. This seeks to maximise the benefit of solar gain in winter, using the thermal mass to absorb gains from south-facing windows, along with heat produced by cooking, lighting, people and appliances. This is then slowly released overnight as the temperature drops, helping to keep the building warm and reducing the need for supplementary heating. By applying simple passive solar design techniques, fuel savings of up to 10 per cent can be made **[10]**, increasing to around 30 per cent where more sophisticated passive solar techniques are adopted such as sunspaces **[11]**.

By applying simple techniques, fuel savings of up to 10 per cent can be made.

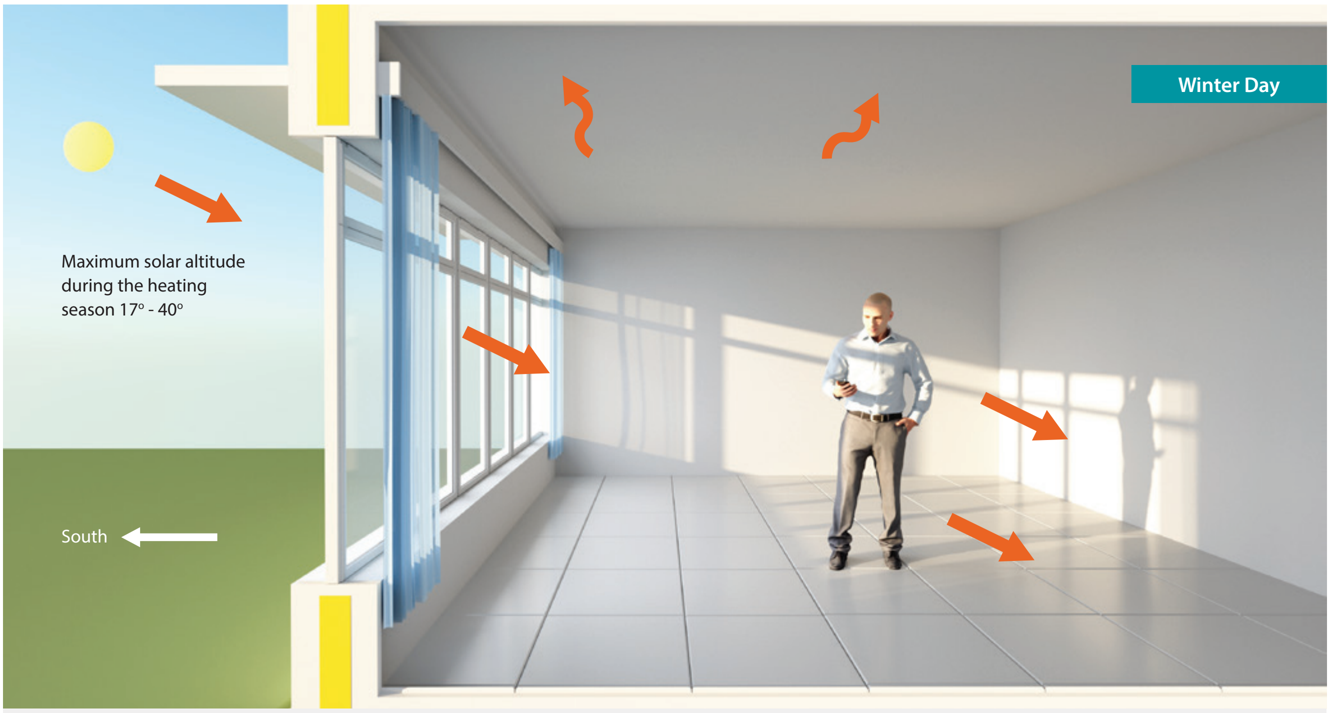
Recent drivers for thermal mass

There are a number of developments that have led to renewed interest in thermal mass and the contribution that it can make to low energy design. These include:

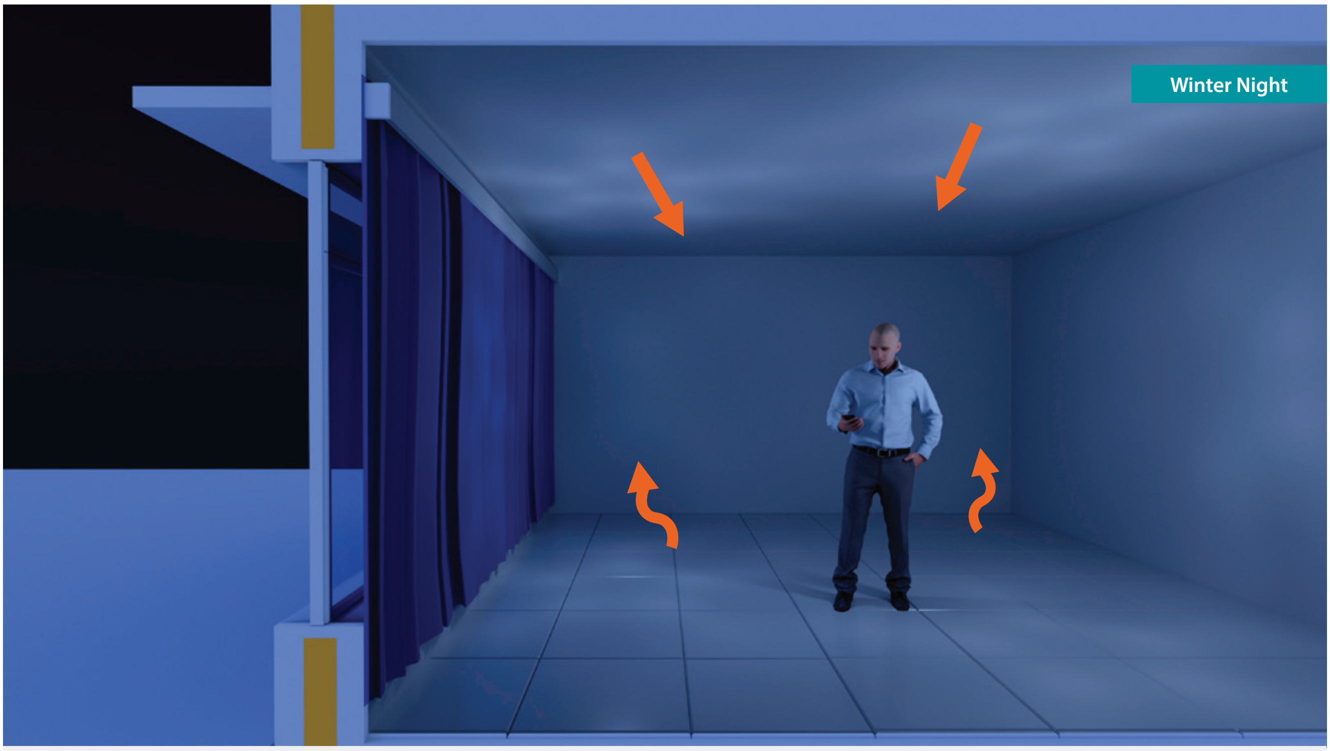
- The increasing risk of overheating as a consequence of a warming climate and the construction of new homes that are highly insulated and airtight.
- Revisions to the Standard Assessment Procedure (SAP) for Part L1 of the Building Regulations and more challenging requirements for addressing overheating in new homes.
- Ongoing improvements in glazing and window technology, which makes passive solar design more effective (lower heat loss and improved solar gain).
- Increasing energy prices and challenging carbon targets, which have refocused efforts to improve energy efficiency in buildings.
- The zero/low carbon policy for new build homes, based on a 'fabric first' approach to design.

East Ham Civic Centre, London has 350mm-thick exposed floor slabs containing pipework for heating and cooling, linked to geothermal boreholes. This works with the floors thermal mass and large surface area to optimise energy efficiency and provide a "simple ceiling approach" unfettered by M&E systems, simplifying the internal spaces. Architect: Rick Mather Architects; Structural Engineer: Engineers HRW. Image © Alamy.

Figure 3: Thermal mass in winter.



- During the heating season, the low angle sun can shine through south-facing windows, and the heat is absorbed by thermal mass in the floor and walls.
- In the evening when the sun goes down and the temperature drops, the heat flow is reversed and passes back into the room.



- At night, curtains are drawn and windows kept shut to minimise heat loss.
- Heat continues to be released by the thermal mass and supplementary heating is adjusted so only the minimal amount is used.
- By morning the thermal mass will have given up most of its heat and the occupants will typically have to rely on supplementary heating until later in the day.

Using thermal mass on a year-round basis

Minimum spacing required between houses of average height:

- Southampton: **20m**
- Leeds: **25m**
- Edinburgh: **30m**
- Inverness: **35m**

Figure 4: House spacing to avoid overshadowing [14]

The use of Passive Solar Design (PSD) provides a simple means of maximising the benefit of thermal mass throughout the year by optimising a building's form, fabric, orientation and ventilation to maximise energy efficiency and comfort.

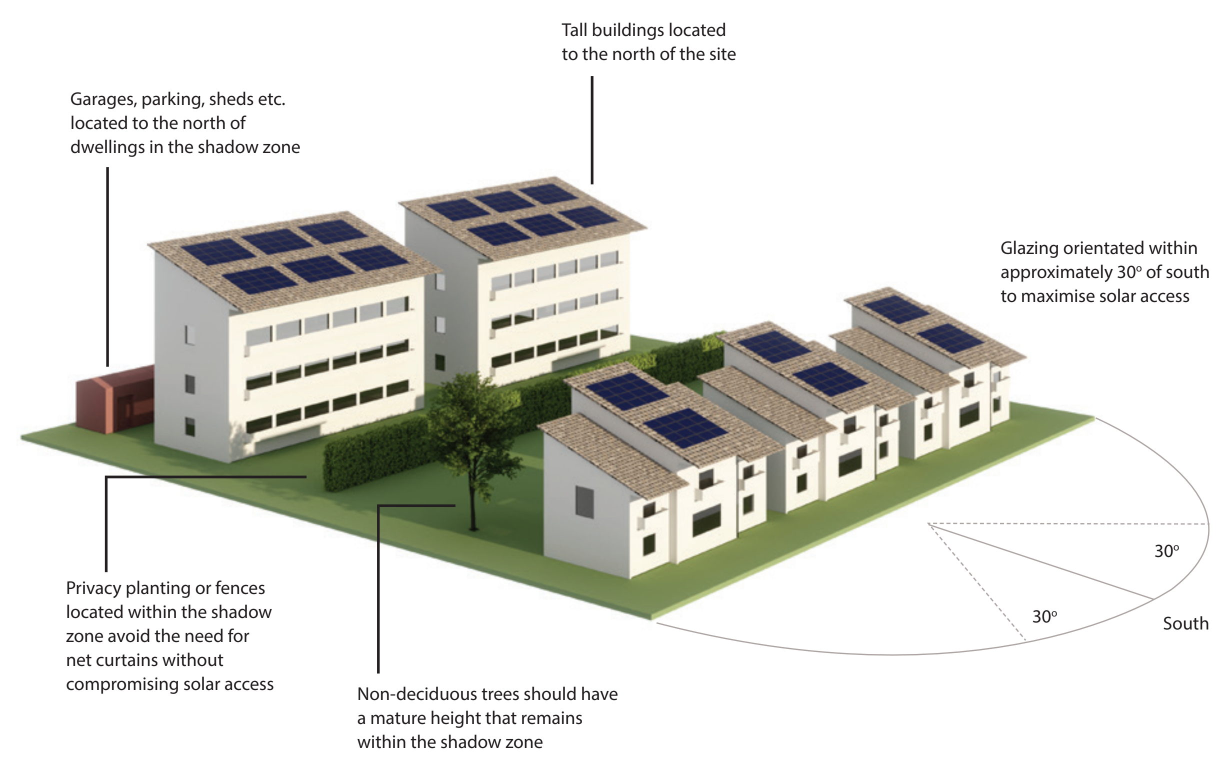
In the UK climate, PSD is mostly used to reduce domestic heating requirements, although it is increasingly being used in non-domestic buildings, where the emphasis is often on maximising daylight without unduly increasing the cooling load. PSD requires a whole-building approach to design, in which the envelope (particularly the glazing) is designed in unison with the structure's thermal mass to ensure optimal admission and absorption of solar gains during the heating season. PSD can be applied with varying levels of sophistication, including the use of both sunspaces and Trombe walls. These systems are beyond the scope of this guide, but plenty of practical information about them can be found online. At a more basic level, the general requirements for applying PSD in housing are outlined here.

Basic requirements

The basic requirements for PSD are:

- A sufficiently clear view of the sky from the south (see Figure 4).
- A high standard of insulation and airtightness that meets or exceeds the requirements of Part L.
- Adequate south-facing windows (or within 30° of south) to maximise solar gains during the heating season (see Figure 5). The optimal area of glazing will be determined by various design issues including cost, ventilation rate and level of thermal mass, but as a very rough guide it should be at least twice that of any north-facing windows, but no more than around 40% of the facade to avoid overheating problems. Low iron glass (clearer than normal glass) can be used to optimise solar gain.
- Minimal north-facing windows to avoid excessive heat loss. Over the course of the year north-facing windows have a net heat loss and should be limited to around 15% of the room's floor area, which is sufficient to provide adequate daylighting.
- A medium to high level of thermal mass. The SAP Thermal Mass Parameter (TMP) should ideally be in excess of 200 kJ/m^{2}K and include a solid ground floor with a finish that partially or fully exposes the floor's thermal mass (see page 15 for information on TMPs).
- An ability to adequately ventilate the building during the summer, taking account of any site specific security and/or noise issues.
- Adequate shading. Overhangs, balconies and brise soleils are particularly effective on south-facing windows, but other forms of shading can be used. Although not popular in the UK, shutters are highly effective, with the added benefit of offering a means of secure ventilation and reduced heat loss in winter.

Figure 5: To maximise solar gain during the heating season, most of a building's glazing should face south or within 30° of south, with minimal overshadowing from around 9am to 3pm.



Thermal mass and insulation

Thermal mass is not a substitute for insulation, and a combination of the two is needed to optimise fabric energy efficiency. The position of the insulation relative to the thermal mass is of particular importance. The simple rule is that the thermal mass should be located inside the insulated building envelope. For this reason, an outer layer of brick offers little benefit, but can help in other ways (see page 17). In practical terms, a masonry cavity wall already satisfies the basic rule, as the insulation is located in the cavity, allowing the inner leaf of blockwork to be exposed to the room. For solid masonry walls, the insulation should be located on the outer surface, which is usual practice. The insulation for solid ground floors should ideally be located under the slab, although screed placed on top of insulation will also provide some useful thermal mass.

There are no hard and fast rules on how much thermal mass is needed, but even a moderate amount, has been shown to provide worthwhile savings **[15]**. From an energy perspective, it would be difficult to have too much, and generally the more thermal mass the better, however, as with all aspects of design it is necessary to arrive at a workable balance, taking other considerations into account. As a rough guide, the surface area of the floor/walls providing the mass should be at least six times that of the glazing in the room **[16]**, although this will to some extent be influenced by the particular properties of the mass i.e. its thermal conductivity and density. So, as the area of south-facing glazing increases, more thermal mass is required to maintain a stable temperature during the summer **[17]**. The depth of thermal mass will also influence performance, and this is discussed later in the document (see pages 14-16).

Figure 7: A tiled floor will allow a concrete floor slab's thermal mass to be fully exploited and is also suited to underfloor heating.

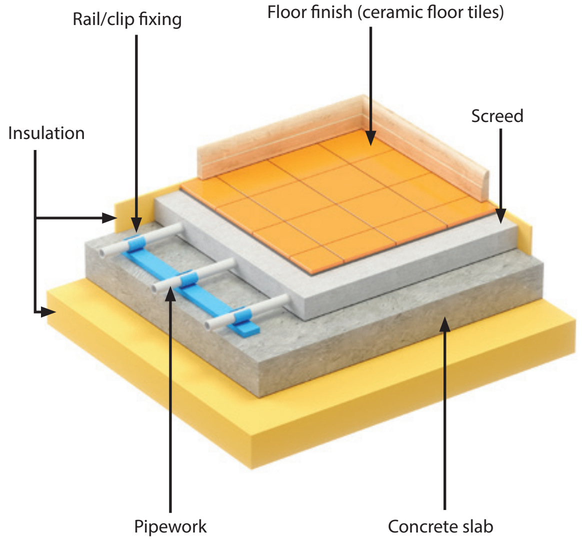


Figure 6: Locating insulation in external walls to maximise thermal mass.

Internal surfaces

Typically, thermal mass is provided by concrete/masonry walls and floors, but other heavyweight materials can be equally effective. It is not essential for the sun to shine directly on all internal surfaces for heat to be absorbed, as convection and radiation between surfaces will help distribute warmth throughout the space. Surfaces do not have to be a dark colour, as any small benefit in heat absorption may impact on daylighting. However, it is important that the surface of heavyweight walls and floors remain as thermally exposed as practicable.

For walls, this is best achieved with a wet plaster finish, as this will conduct heat relatively freely and offers the added benefit of providing a robust air barrier that will help minimise air leakage. Dry lining will reduce heat flow, but its impact will depend on the thermal mass potentially available in the wall. For an aircrete block inner leaf (which has a relatively low thermal conductivity), plasterboard is less of a thermal bottleneck than for heavier weight aggregate blockwork, which has higher thermal conductivity and is more sensitive to the choice of finish. Therefore, to fully exploit the high level of thermal mass available in aggregate blocks, the use of dry lining is best avoided.

With some forms of concrete wall and floor construction, it is possible to achieve a high quality, fair-faced finish which requires little more than a coat of paint. From a thermal mass perspective, this is particularly beneficial as heat can pass directly between the room and the concrete. Although not often used in residential buildings, a fair-faced finish is more common in low energy commercial offices or schools where an exposed concrete soffit is used to provide thermal mass.

Wherever practicable, ground floors should be tiled, and the use of carpet minimised, as placing carpet on a concrete floor can reduce its ability to admit heat by half **[18]**. A shiny or glossy floor finish will absorb less heat than a dull finish, however, this must be evaluated alongside daylighting requirements and the tendency of such a surface to absorb light. A tiled floor also works well with underfloor heating, which in turn can be particularly efficient when designed with a high level of thermal mass in the slab and a heat pump or condensing boiler to provide a continuous source of low grade heat **[11]** (see Figure 7). Solid upper floors also provide a good medium for underfloor heating, whilst adding additional thermal mass to the building. If carpet/underlay is used, it should have a tog rating of 1.5 or less so heat flow is not unduly restricted.

Internal layout

Where practicable, the most frequently used rooms should be on the south side of the dwelling, so that they enjoy the greatest benefit to be had from solar gain during the heating season. Bathrooms, utility rooms, hallways, stores etc. should be located on the north side of accommodation **[19]**. The cooling benefits from thermal mass tend to be slightly lower in bedrooms than for the general living spaces. So, in southern England where summer temperatures are highest, there may be some benefit in locating bedrooms on the north side.

Another option that can help is to specify a concrete upper floor. Providing the mass remains reasonably accessible, this can improve year-round thermal performance. A further option is to locate south-facing bedrooms on the ground floor, so they get the full benefit of stack ventilation at night. The stack effect uses the difference in air temperature at high and low level to draw cool night air into ground floor rooms, where it then travels upwards through the building and exits from windows on the upper floor(s), having absorbed heat from the building fabric on route. A house designed to take advantage of stack ventilation will benefit from more consistent air flow, particularly on still nights.

Intermittently heated buildings

Older heavyweight buildings with comparatively low levels of insulation and minimal solar gain in winter, have traditionally required a longer pre-heat period than lightweight buildings, resulting in slightly higher fuel consumption. However, the greatly improved standard of insulation and airtightness in new construction means this is no longer the problem it once was, as the fabric remains relatively warm when the heating is off, reducing the amount of pre-heat needed to get the building back up to temperature. It is also worth noting that the pre-heat issue only applies to intermittently heated buildings, and in reality a low level of continuous heating is the preferable option in heavyweight buildings. However, in some types of intermittently occupied buildings, for example weekend holiday cottages, thermally lightweight construction will enable a more rapid warm up period, although summertime comfort may be less favourable.

Night cooling

During the hot summer months, the building fabric must be cooled during the night by ventilation to remove the heat that has been absorbed during the day. Night ventilation requires careful design to ensure adequate air flow can be achieved, and to address any acoustic, air quality or security issues that may arise.

Thermal mass and overheating

As homes become more highly insulated, fabric heat loss potential is reduced and heat flow balances become much finer; a small excess of heat gain over heat loss can lead to overheating **[25]**. Thermal mass can be useful in smoothing out these gains and losses, and in so doing help to stabilise the internal temperature.

This is particularly beneficial during the hottest part of the day (i.e. the afternoon) when occupants are likely to include mothers with young children and older/retired people, who are particularly susceptible to heat-related illness. It is important to note however, that without adequate provision for night ventilation, the presence of thermal mass may contribute to the risk of overheating, as it will become saturated with heat, which will have no where to go except back into the occupied space **[27]**.

The combined benefit of thermal mass and night ventilation is accounted for in the Standard Assessment Procedure (SAP) overheating check for new dwellings, which gives a reduction in the peak internal temperature of up to 3.5K when comparing lightweight and heavyweight construction (see Figure 8).

Measuring thermal mass

Admittance values

Describing a material as having high, medium or low thermal mass gives a useful indication of its ability to store heat, as does its k-value, but in order to know how effective a chosen material will be in practice, there are a couple of other important factors that need to be taken into account. These are firstly the length of time available to get heat in and out of the material, which is typically assumed to be 24 hours (i.e. heating during the day and cooling at night), and secondly, the resistance to heat flow at the surface of the material, which can be significant. These factors are both accounted for in admittance values, along with thermal capacity, conductivity and density. Admittance values provide a practical means of assessing the approximate in-use heat absorption performance of walls and floors etc.

From a technical perspective, admittance can be defined as the ability of a material or construction element to exchange heat with a space when it is subject to cyclic variations in temperature. Admittance is measured in W/m^{2}K, the same as U-values. However the 'K' represents something different i.e. the difference between the mean internal temperature and the actual temperature at a specific time of day. It is this dynamic temperature difference that drives heat in and out of the fabric. In contrast, the 'K' in U-values is the difference between internal and external temperature, which is assumed to be constant, which is why U-values are steady state. Another difference is that high admittance values are desirable from a thermal mass perspective, whilst low U-values will minimise heat loss.

Limitations of admittance values

Admittance values allow a comparison to be made of the heat absorption characteristics of materials in response to a simple heating and cooling cycle. However, caution must be taken if this approach is used to assess overall building performance as it can underestimate the actual peak cooling capacity of a high thermal mass structure by up to 50 per cent in comparison to more sophisticated thermal modelling techniques that use real weather data **[20]**. A more detailed explanation of this follows.

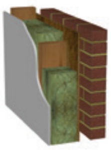
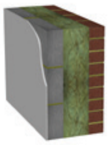
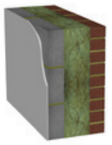
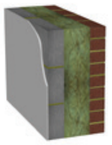
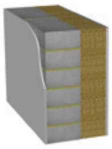
Effect of longer heating/cooling cycles

In addition to a building's daily heating and cooling cycle, there is often a cycle related to a typical UK peak design weather period (usually three to five days) and also the five working days per week cycle, from which heat will reach different depths within the available thermal mass. In the case of floors in a non-air conditioned building for example, the greater the slab depth, the longer the time period it responds to; the core of a 300mm thick concrete slab responds to the monthly average condition and draws heat in deeper over an extended period of hot weather **[20]**. For longer time periods these factors are important because it is the longer-term average room temperatures that define the thermal storage core temperature and hence the temperature gradient that draws heat in. It is for this reason that only a detailed thermal analysis will show the effectiveness of medium and high depth floor slabs and walls under real conditions.

Upper limit of admittance values

In naturally ventilated buildings, the resistance to heat flow at the surface of the floors and walls limits admittance values to a maximum of around 8 W/m^{2}K **[22]** even in very heavyweight construction. This is because although concrete and other heavyweight materials have moderate thermal conductivity, they are often limited by the rate of heat transfer at the surface which may act as a bottleneck. To some extent, this can be overcome in mechanically ventilated buildings, as discussed in the section on effective slab depth in commercial buildings (see page 16).

Table 2: Admittance, decrement and k-values for some common types of wall construction [21]. A more comprehensive table of values, including floors, can be found in The Concrete Centre publication: Thermal Performance Part L1A. Download it at: **www.concretecentre.com/publications**

External wall (U-value = 0.25 W/m^{2}K)	**Timber frame (Brick outer leaf)** 		**Masonry cavity wall (100mm aircrete block)** 		**Masonry cavity wall (100mm lightweight aggregate block)** 		**Masonry cavity wall (100mm dense aggregate block)** 		**Solid masonry (215mm lightweight aggregate block)** 	
Internal finish	Plaster-board	Wet plaster	Plaster-board	Wet plaster	Plaster-board	Wet plaster	Plaster-board	Wet plaster	Plaster-board	Wet plaster
Decrement delay (hours)	7.5	-	10.65	10.2	11.21	10.51	10.67	10.00	11.79	11.6
Decrement factor	0.56	-	0.26	0.33	0.16	0.25	0.13	0.23	0.08	0.11
Admittance value 24 hour cycle (W/m^{2}K)	1.00	-	1.85	2.65	2.38	4.05	2.65	5.04	2.24	3.7
k-value (kJ/m^{2}K)	9	-	52	65	114	141	154	190	114	141

k-values and Thermal Mass Parameter

Part L of the Building Regulations and its associated compliance tools (SAP & SBEM) account for thermal mass using k-values (kJ/m²K), which represents the heat capacity per square metre of floor or wall. They are measured from the inside surface stopping at which ever of the following conditions occur first:

- halfway through the construction element
- an insulating layer (thermal conductivity less than 0.08 W/mK)
- a depth of 100mm

In addition to the k-values shown in Table 2, generic values for different construction elements can be found in SAP Table 1e and also in The Concrete Centre publication: Thermal Performance: Part L1A. SAP calculates a dwelling's overall thermal mass by multiplying the surface area for each construction element by its k-value and adding the results. The total is then divided by the floor area of the dwelling to give the Thermal Mass Parameter (TMP) measured in kJ/m²K, where 'm²' refers to the dwelling's floor area.

Table 3 shows what is considered in SAP to be low, medium and high levels of thermal mass. Table 4 shows the approximate TMP for a typical end-terrace house built using a range of materials and finishes.It should be noted that the TMP varies to some extent with the size and type of dwelling.

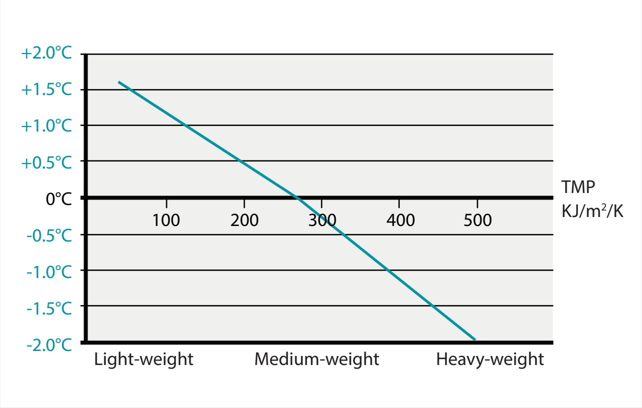


Figure 8: SAP overheating check – reduction in internal temperature for light, medium and heavyweight homes with night ventilation.

Thermal mass of dwelling	TMP (kJ/m²K)
Low	100
Medium	250
High	450

Table 3: Indicative Thermal Mass Parameters (TMP) used in SAP.

Table 4: TMP for a typical end-terrace house.

House construction	Timber ground floor	Concrete ground floor	Stud partitions	Block partition	Timber upper floor	Concrete upper floor	Approximate Thermal Mass Parameter (kJ/m²K)
Timber frame	✓		✓		✓		60 - 80
Timber frame		✓	✓		✓		90 - 120
Masonry (600 kg/m³ blocks)		✓	✓		✓		160 - 220
Masonry (600 kg/m³ blocks)		✓		✓	✓		190 - 240
Masonry (600 kg/m³ blocks)		✓		✓		✓	250 - 370
Masonry (1400 kg/m³ blocks)		✓	✓		✓		270 - 350
Masonry (1400 kg/m³ blocks)		✓		✓	✓		340 - 420
Masonry (1400 kg/m³ blocks)		✓		✓		✓	400 - 540
Masonry (2000 kg/m³ blocks)		✓	✓		✓		340 - 430
Masonry (2000 kg/m³ blocks)		✓		✓	✓		430 - 530
Masonry (2000 kg/m³ blocks)		✓		✓		✓	500 - 650

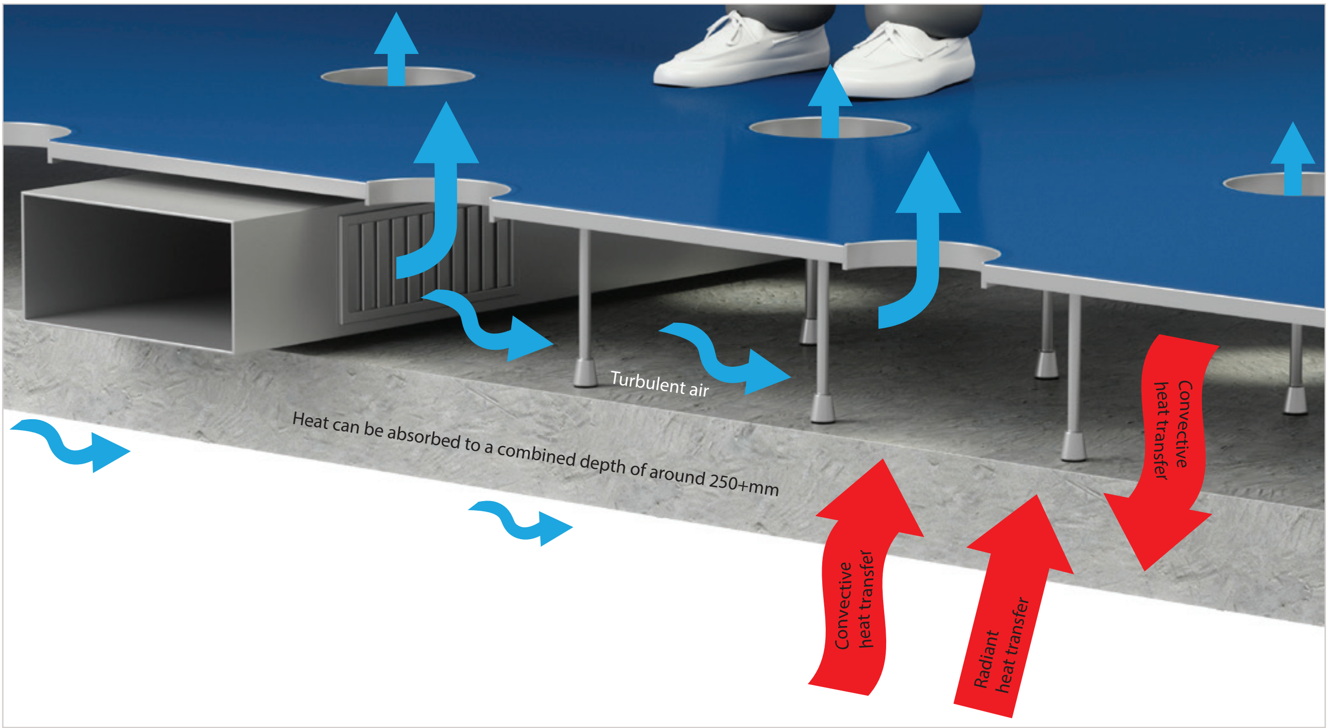


Figure 9: Combining an exposed soffit with optimised underfloor ventilation can enable thermal mass to be reached at a total slab depth of 250mm and more.

Effective slab depth in non-residential buildings

As the building fabric becomes an increasingly important aspect of low energy design, floor slabs are shifting from being purely a structural element to something that contributes to a range of other design issues including aesthetics, daylighting, acoustics and thermal performance. Structural requirements will of course largely determine slab depth, although thermal mass may, to some extent, also be a factor. For a non air-conditioned building, the core of the slab will respond to daily, weekly and monthly average conditions, drawing heat deep into the concrete and making use of most, if not all of the slab (see page 14). In air-conditioned buildings, plant is generally operated on a 24 hour heating/cooling cycle which in turn governs the time available for getting heat in and out of the slab. However, it is still possible to take advantage of a large proportion of the thermal mass in the slab. This is explained below.

Using both sides

In offices with mechanical ventilation, the air supply often comes from floor outlets linked to an underfloor distribution system, where the void created by the raised floor is used to channel air around the space. In addition to reducing the need for ductwork, this approach also allows convective heat transfer between the air and the floor slab (see Figure 9). This helps cool the air supply during the day and remove heat from the slab at night. When used in conjunction with an exposed soffit, heat can pass through both the top and bottom surfaces of the slab, increasing the overall depth of concrete in which the thermal mass can be accessed.

Enhancing heat flow at the surface

Before heat can enter the slab it must first pass through its surface, which acts as the main bottleneck to heat flow due to a film of air (boundary layer) that clings to it and has an insulating effect. The boundary layer provides a greater resistance to heat flow than the concrete itself. However, in buildings with mechanical underfloor ventilation, the system can be designed to ensure some turbulence as the air passes over the slab, which helps strip away the boundary layer, greatly reducing surface resistance and enhancing heat transfer by a factor of up to five **[23, 24]**. This allows thermal mass to be exploited at greater slab depths than would otherwise be possible. Turbulent air is also a feature of systems that use the cores in hollowcore precast concrete floor slabs to channel the supply air (e.g Termodeck®), ensuring good heat transfer particularly at bends where the change of direction increases turbulence.

Profiled soffits

In addition to reducing the weight of larger spans, profiled slab soffits (e.g. coffered, troughed, wave form etc.) provide an increase in surface area which improves convective heat transfer with the slab, allowing greater use of the thermal mass.

Floor slabs are not purely a structural element – They also contribute to other design issues including aesthetics and thermal performance.

Decrement values

Like U-values and admittance, decrement is a term that represents a specific characteristic of construction materials, and is related to thermal mass. It describes the way in which the density, heat capacity and thermal conductivity of a wall for example, can slow the passage of heat from one side to the other (decrement delay), and also attenuate those gains as they pass through it (decrement factor).

Decrement delay

Designing for a long decrement delay of around 10 to 12 hours will ensure that during the summer, peak heat gains passing from the outer to inner surface will not get through until late evening/night, when the risk of overheating has moderated, and the relatively cool night air can offset the effect of a warmer surface. Shorter periods can still be helpful but effectiveness reduces with decreasing delay, and a value of less than around six hours is of limited benefit.

Medium and heavyweight walls insulated to current standards will slow the passage of heat by around 9 to 12 hours (see Figure 10), which provides an optimal level of decrement delay. Lighter-weight construction typically provides a shorter period ranging from just a few hours up to around 7 or 8 hours, usually in walls with a masonry outer leaf (see Table 2 for decrement values of typical wall constructions).

Decrement factor

As well as delaying heat flow on summer days, the dynamic thermal characteristics of a wall or roof construction will also determine the effect heat reaching the internal surface will have on its temperature stability. This is represented by the decrement factor, which is basically the ratio between the cyclical temperature on the inside surface compared to the outside surface. For example, a wall with a decrement factor of 0.5 which experiences a 20 degree daily variation in temperature on the outside surface, would experience a 10 degree variation on the inside surface. So, a low decrement factor will ensure greater stability of the internal surface temperature, and is another means of helping reduce the risk of overheating. Medium and heavyweight walls insulated to current standards have a low decrement factor of around 0.3 to 0.1 (see Table 2). Using the previous example, a decrement factor of 0.1 would cause the inside surface temperature to vary by only two degrees over the day. For lightweight walls, the decrement factor will typically be in the order of 0.5 to 0.8, with the lower end of this range often found in walls with a masonry outer leaf.

Heat gains through windows and from internal sources

In well insulated lightweight construction the risk of overheating can be more acute, since the balance of heat flows is much finer and only a small excess of heat gain can cause overheating **[25]**. So, the decrement factor and delay can be of more significance, and it is possible to enhance these slightly by using cellulose (wood-based) insulation, which has a relatively high heat capacity and density compared to most other forms of insulation.

However, for all types of building, delaying and reducing gains passing through the fabric is only part of the solution, as instantaneous heat gains through windows and from internal sources must still be managed and are generally of much greater significance. In addition to good shading and ventilation, the impact of these gains will be reduced through the presence of internal thermal mass to help soak them up (see Figure 2 and page 6), which is a key benefit of medium and heavyweight construction.

Figure 10: On hot days, internally exposed thermal mass helps counter the impact of heat gains from windows and internal sources. At the same time, the overall mass and insulation provided by the external walls reduces and slows heat gains passing through them, helping ensure that any effect they may have on the internal environment does not occur until late evening/night when the risk of overheating has moderated.

Solar gains result in a peak external surface temperature at around 2.00 - 3.00pm

Internally exposed thermal mass absorbs heat, reducing the impact of any daytime gains from windows, appliances and people etc.

The combination of insulation and thermal mass (at any point in the wall) minimises the heat passing through and also provides a significant time lag, so the peak internal surface temperature occurs many hours later.

Mass enhanced U-values

U-values indicate the rate of heat flow through a construction element for a given difference between internal and external temperature, which is assumed to be constant, i.e. steady state. Generally this will give a good indication of the insulating properties of a wall, roof or floor, but can be less accurate in climates where the outdoor temperature may cycle above and below the internal temperature over a 24 hour period. In this situation, the actual heat loss of a heavyweight external wall can be less than its U-value would suggest. The reason for this is because the heat flow through the wall is not constant (steady-state), nor is it only in one direction i.e. from inside to outside. The direction will in fact change each time the external temperature cycles above or below the internal temperature. In this situation the performance of the wall is no longer simply a question of how much insulation it contains, but is also influenced by its level of thermal mass; at night, when the temperature drops, heat begins to flow through the wall to the outside. But the presence of thermal mass will slow this process (decrement delay) and, the following day when the temperature outside becomes greater than that inside, the direction of heat flow is reversed allowing some of the heat retained by the thermal mass to flow back into the room.

This mass enhanced effect is real and a heavyweight wall can thermally outperform a lightweight wall with the same steady-state U-value. The effect is most significant when the outdoor temperature cycles above and below the indoor temperature in a 24 hour period **[26]**.

Summary

Performance requirements for building materials continue to increase, driven by a need to design for higher levels of energy efficiency and other factors such as the effects of climate change. Meeting these challenges requires a whole-building approach to design in which the materials, structure and systems work in unison to maximise overall performance. The thermal mass in concrete and masonry helps to meet this challenge. It can both improve energy efficiency in summer and winter, whilst also providing a degree of adaptation to our warming climate.

Dynamic Thermal Properties Tool

Whilst published thermal mass values are available for generic walls and floors, these won't necessarily be valid for bespoke constructions. To address this limitation, The Concrete Centre commissioned Arup to produce a simple Excel-based tool to help designers. The thickness of each material used is specified, along with its thermal conductivity, density and heat capacity, all of which can be obtained if necessary from a reference table included in the tool. Having entered the details of a construction the following results are provided:

- Admittance value
- k-value
- Decrement delay
- Decrement factor
- Basic U-value
- Other admittance related information.

The methodology used follows European Standards for calculating thermal proprieties, and k-values produced can be used in SAP and SBEM (the compliance tools for Part L of the Building Regulations). The tool and instructions for its use can be downloaded without charge at: **www.concretecentre.com/publications**

Slip House, Brixton. The inherent thermal mass of the floor helps moderate the internal temperature as the exposed concrete floors act as a thermal sponge, absorbing heat on warm days, and releasing it at night. Image © Cornish Concrete Products.

The state-of-the-art Three Rivers Academy, Walton-on-Thames used exposed fair-faced concrete soffits, together with an extensive roof-mounted range of photovoltaic panels which helped the school achieve an energy performance certificate rating of A. Architect: Scott Brownrigg; Structural Engineer: Arup. Image © Hundven-Clements Photography

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The Concrete Centre, Gillingham House, 38-44 Gillingham Street, London SW1V 1HU

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Written by Tom de Saulles BEng CEng MCIBSE MIMechE