General guidelines for using thermal mass in concrete buildings

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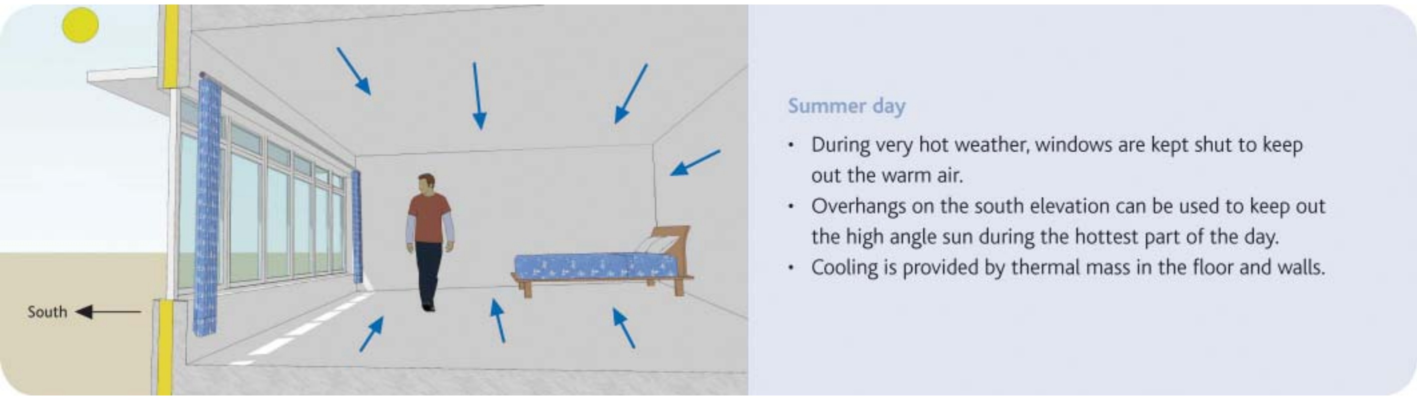
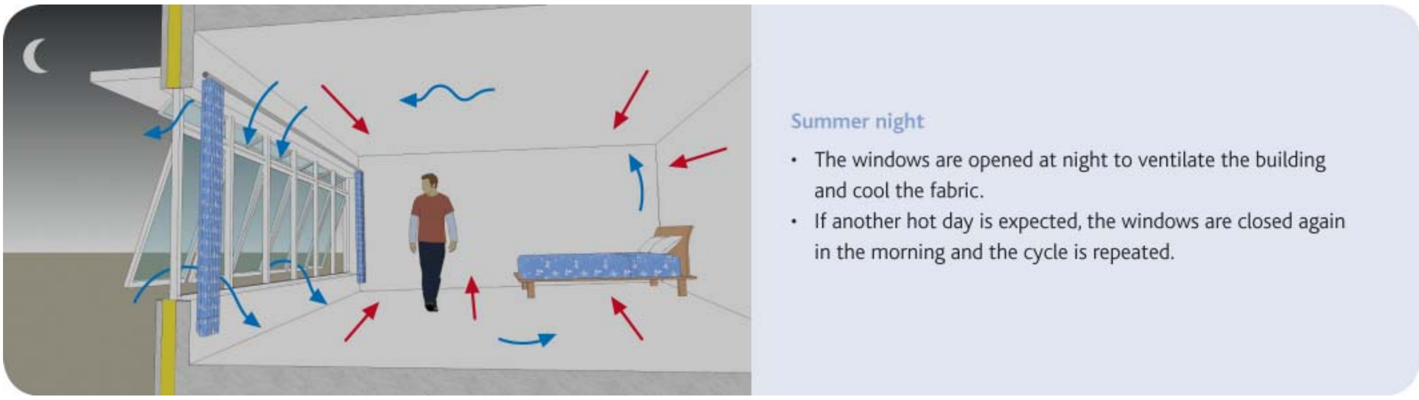
In warm climates, the thermal mass in concrete and masonry helps provide a comfortable living environment and reduce overheating problems, whilst in cooler climates it can be used to absorb solar gains and reduce the need for heating energy.
As the basic design requirements for both seasons are not incompatible, housing in more temperate climates can be designed to take advantage of thermal mass on a year–round basis. Examples of such regions include much of northern Europe and the UK. For case studies and more information on the benefits of thermal mass visit: www.cembureau.eu/default.asp?p=Case_studies01.asp

Cooling - During hot weather, the thermal mass in concrete and masonry housing will soak up internal heat gains, helping stabilise the temperature and maintain comfortable conditions. This is because the high thermal capacity of the building fabric allows a great deal of heat to be absorbed with only a small increase in the internal surface temperature of the walls/floors. As a result, the surface temperature stays below that of the ambient air for much of the day, resulting in both radiant and convective cooling of the occupants. At night, the heat absorbed by the walls/floors is removed by using the relatively cool night air to ventilate the building, enabling the house to repeat the cycle the following day. The risk of overheating can be further reduced by locating an overhang above south facing windows to shade them from the sun during the hottest part of the day. This is of course a well understood approach to design in the warmer parts of Europe, but is also becoming increasing relevant in other regions where the impact of climate change is beginning to increase peak summertime temperatures.





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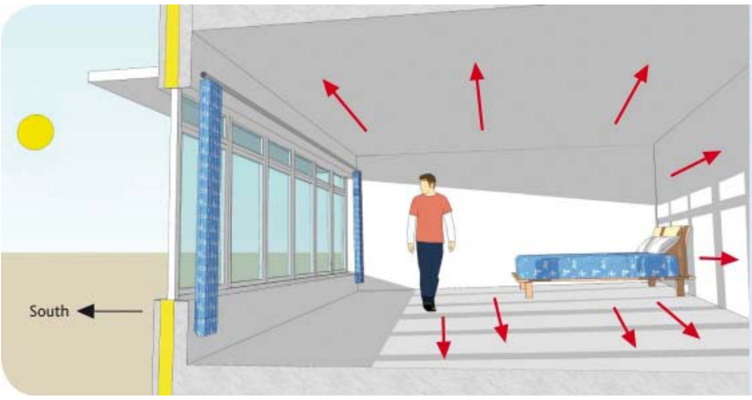
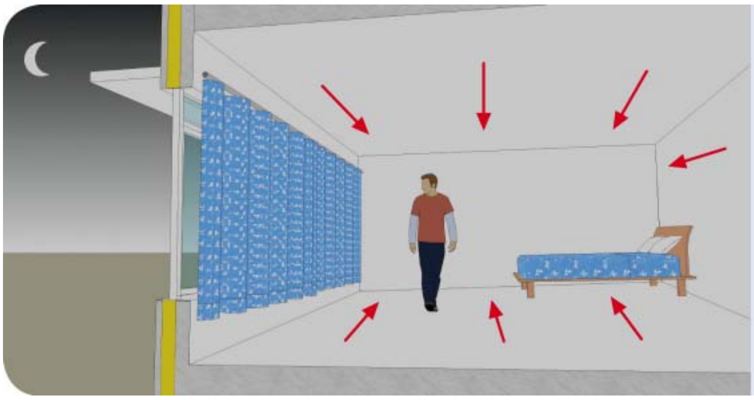
Heating - During the heating season thermal mass can be used to reduce fuel requirements, by allowing the low angle winter sun to shine into the building through the south facing windows during the warmest part of the day (shading overhangs are only effective during the summer). The solar gains are absorbed by thermal mass in the floors and walls, and then slowly released at night as the temperature drops. This heating and cooling cycle is similar to that used in the summer, the difference being that solar gains are encouraged during the heating season as this is useful heat, and windows are kept shut at night to minimise heat loss.



Winter day

- 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.



Winter night

- 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.

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DESIGN CHECKLIST FOR YEAR-ROUND USE OF THERMAL MASS

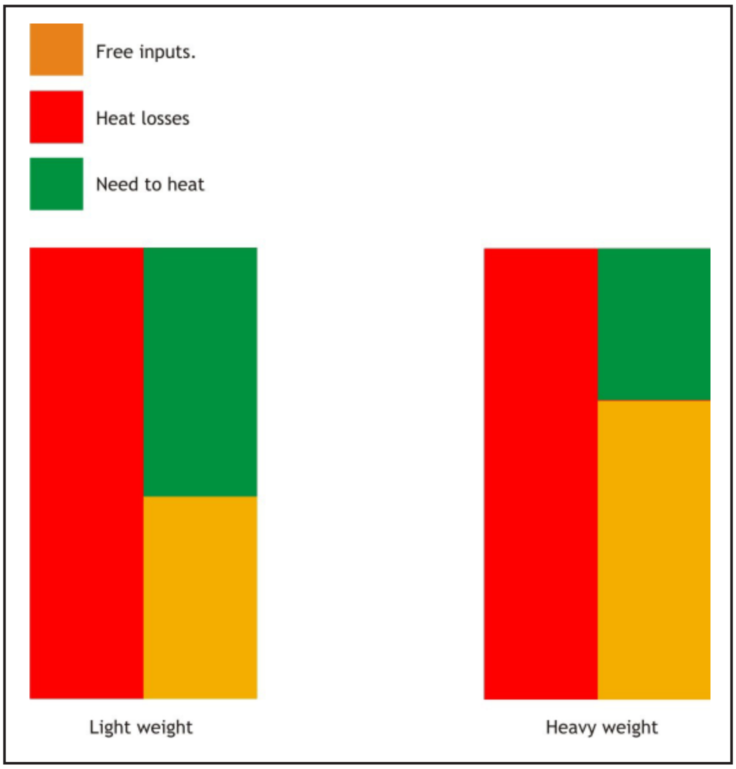
Orientation - Dwellings should be orientated towards the south, or within about 30° of south, to maximise solar gain during the heating season and to simplify shading in the summer through the use overhangs, balconies, brise soleils etc.

Windows – where heating is the main consideration, the basic requirement is for relatively large south facing windows and relatively small north facing windows (over the course of a year, north facing windows generally have a net energy loss). The area of south facing glazing will need to be sized to take account of a range of factors including the insulation performance of the glass, level of thermal mass, and general design requirements for the dwelling. Windows that are too large may be counter productive as their heat loss on winter nights can outweigh their ability to capture solar gains during the day. They may also lead to an increased risk of overheating during the summer. As a rough guide, windows should be at least 15% of a room's floor area to provide adequate daylight, and not more than 40% of the façade area if excessive heat gain/loss is to be avoided[1]. Larger areas may be possible with triple-glazing or specially coated high performance glass. Whilst large south facing windows are preferable, worthwhile savings can still be achieved with a conventional area of glazing. If cooling performance is the main consideration, a more modest window area will reduce solar gains, however they should still be of a sufficient size to allow adequate daylighting.

Room layout – For optimal passive heating, the most frequently used rooms should be on the south side of the dwelling so 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.

View of the sky – To maximise solar gain during the heating season, the southern façade should have a relatively clear view of the sky to allow solar radiation from the low angle winter sun to pass directly into the building i.e. underneath any shading overhangs. To maximise the view of the sky, adjacent buildings and structures creating an obstruction angle greater than around 30° above the horizon should be avoided: Every percentage point increase in obstruction over 30° results in roughly the same percentage point increase in energy use[2]. New housing developments provide the best opportunity for optimisation as a sympathetic layout can often be adopted.

Indirect solar gains - Where obstructions limit the amount of direct solar radiation to be captured, some heat is still obtained from diffuse radiation, and also reflected radiation from the ground (especially from light coloured paving), as well as from adjacent buildings. It is a common misconception that passive solar design only seeks to maximise the amount of direct sunshine entering a building.



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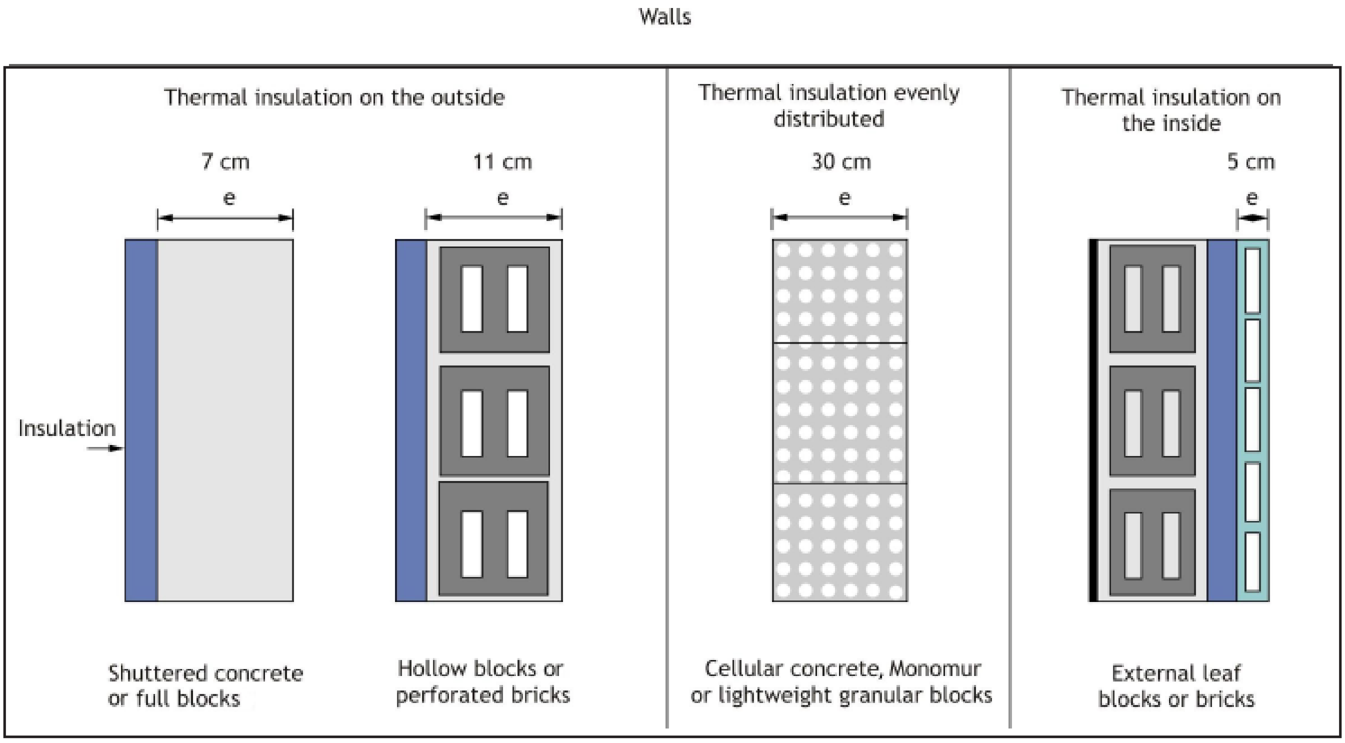
Shading – An overhang of around 0.5 to 1.5m (depending on window height) will block the high angle sun during the hottest part of the summer. During the heating season, overhangs will not obstruct the low angle sun, which is able to shine directly into the dwelling. This very simple form of shading requires no user control, but does not offer some of the additional benefits of other shading systems such as glare control and the added insulation provided by shutters on cold nights. Overhangs may therefore be best used in combination with other forms of shading to optimise year-round performance.

Thermal mass and insulation – In most climates, both thermal mass and insulation are important factors in optimising the thermal performance of buildings. The positioning of thermal mass in relation to the insulation will result in distinctively different responses, and as far as practicable, the internal surfaces of heavyweight walls floors and ceilings should be left thermally exposed to aid heat absorption. Internal finishes such as plasterboard and carpet will to some extent act as a barrier to heat flow by acting as an insulating layer. The insulation in external walls should be located behind the concrete/ masonry inner leaf. Some types of concrete wall construction may use interior insulation in conjunction with a thermal break; however a significant level of thermal mass can still be achieved within such a building if concrete floors are used. The simple rule for maximising thermal mass is that, as far as practicable, concrete floors and walls should be left thermally exposed inside the building e.g. use finishes such as paint, tiles, or plaster.

In warmer climates where cooling is the main consideration, thermal mass performs another function: In addition to absorbing heat gains through windows and from internal sources (as previously described), it will also slow and reduce the conduction of heat gains through external walls and roofs. Heavyweight construction is particularly good at doing this. If the gains are delayed sufficiently, they will not be felt until the evening/night-time, when the risk of overheating will have moderated and the cooler night air should be sufficient to offset the slightly warmer internal surfaces. To take full advantage of this effect, the objective is to design for an appropriate time lag.

For east facing walls a very short or very long delay is generally best, however the latter requires a very thick wall which may not be practicable. For south facing walls a lag of around 10 -12 hours will delay the midday heat until late evening/night. The same delay or slightly less (8 hours) is also suitable for west facing walls since there are only a few hours to sunset. North facing walls have little need for a time lag as the solar gains are small. For roofs exposed to solar gains all day, the time lag needs to be very long to delay the penetration of heat until the evening. However, this is often impracticable, as it requires very heavyweight construction, so the use of additional insulation is typically a better option[3].

Typical options for walls



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Ventilation – For optimal summertime performance rooms should be designed to enable cross ventilation, which is particularly effective for night cooling. This is achieved by locating windows on adjacent sides of a room to maximise air flow. Single-sided ventilation, where the air enters and leaves via one or more windows located in the same wall, is less effective but still adequate for smaller rooms, especially if the window(s) provide a relatively large free area when opened. The optimum ventilation rate for night cooling depends on the specific characteristics of the dwelling, but for maximum effect there should be up to ten air changes per hour. Higher air change rates may improve the cooling rate, but only to a limited extent. This is because the cooling rate is also affected by the length of time the air is in contact with internal surfaces; high air change rates result in less contact time.

Occupant control - The basic control strategy on hot days is for windows to remain closed to prevent warm air entering the dwelling, and shading to be used to limit direct solar gain. Cooling is provided by the thermal mass. In the evening when the ambient temperature drops below the internal temperature, windows are opened to provide night-time ventilation and cooling of the building. During the heating season, windows are kept shut, with ventilation provided by trickle vents or some other form of controlled background ventilation. Where applicable, shutters, blinds, curtains etc. can be used to reduce heat loss from windows at night.

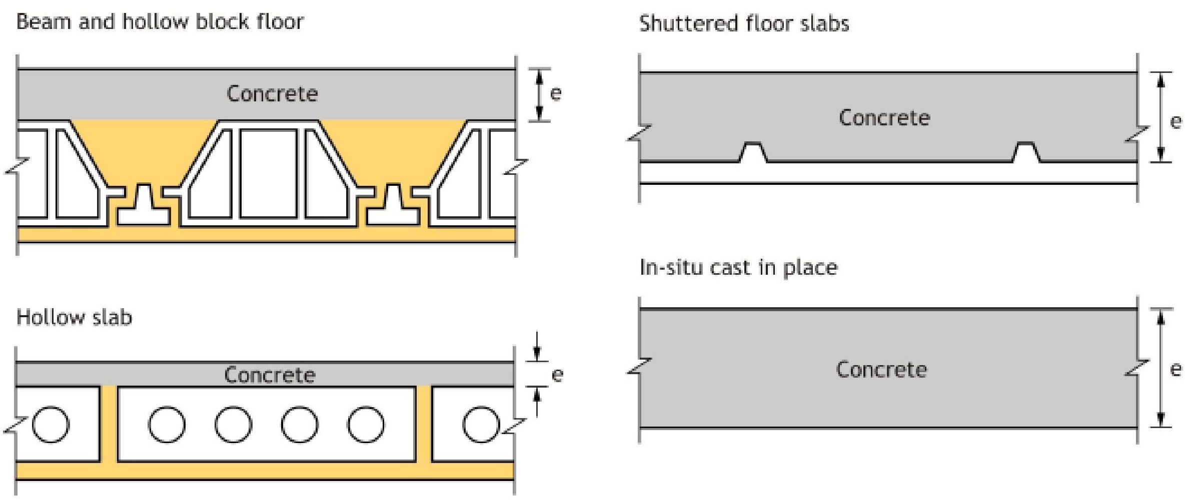
Architectural appearance - A common misconception about passive solar design and the use of thermal mass generally is that it results, of necessity, in dwellings of unconventional appearance which do not fit comfortably into the townscape. However, this is not the case, and passive solar features can be introduced into existing ranges of volume house design without major changes in appearance, cost or marketability[4].

The use of concrete to provide thermal mass in offices and commercial buildings is a well established approach to passive cooling, which can also enhance the buildings' structural and visual qualities. The mass is typically provided by the floor slab which will have an exposed soffit and/or an underfloor ventilation system. The slab provides a large heat sink to counter the relatively high internal heat gains from equipment and lighting etc. As with other high thermal mass buildings, the internal environment responds slowly to changes in ambient temperature, helping stabilise conditions during warm weather. This is assisted by the relatively low radiant temperature of the exposed concrete, which helps maintain a comfortable working environment, allowing higher air temperatures to be tolerated than would otherwise be possible.

Cooling - In addition to reducing peak temperatures by absorbing internal heat gains, thermal mass also delays its onset by up to six hours. In an office environment this is particularly beneficial as the peak temperature will typically occur in the late afternoon, or the evening after the occupants have left. At this point the warming cycle is reversed, with solar gains greatly diminished and little heat generated by occupants, equipment and lighting. As the evening progresses the drop in external air temperature makes night ventilation an effective means of removing the accumulated heat, so the cooling cycle can continue the following day.

Heating - The ratio of cooling to heating tends to be high in offices and commercial buildings as a result of the significant internal loads from lighting, equipment and people. This makes the summertime performance of thermal mass the main consideration in this type of environment. The effectiveness of passive solar design for heating may also be limited by the occupancy pattern of office environments, which is typically limited to the daytime. However, the basic design principle can still be used to maximise daylighting without unduly increasing the risk of overheating from solar gains.

Typical options for floors



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DESIGN CHECKLIST FOR THERMAL MASS IN OFFICES AND COMMERCIAL BUILDINGS

Passive and active systems - For well shaded, low occupancy buildings, the combination of thermal mass and natural ventilation from windows can be sufficient to provide comfortable internal conditions and avoid overheating problems. More demanding environments may require the addition of mechanical ventilation to increase the cooling capacity and improve year-round control. This will often take the form of a 'mixed-mode' system which optimises the use of passive and mechanical ventilation throughout the year. Another option is water-cooled floor slabs, also know as thermo-active concrete, which provides a hybrid approach that maximises cooling performance and can take advantage of natural water sources. For environments where conventional air-conditioning cannot be entirely avoided, thermal mass can still provide a means of significantly reducing energy consumption, and can shift the load to the night-time when it is generally cheaper to run the plant.

Optimal slab thickness - Floor slabs will typically provide most of the thermal mass and, to some extent their thickness will determine the cooling performance. Whist floor spans and loading are what largely determine thickness, the following points should also be noted:

- It is generally accepted that heat will penetrate up to 100mm into concrete during a simple 24 hour heating and cooling cycle. However, for longer cycles i.e. that experienced during an extended period of hot weather, greater depths can be advantageous as the increased heat capacity delays or avoids the concrete becoming saturated with heat.

- A slab thermally exposed on the upper and lower surface (e.g. exposed soffit and underfloor ventilation), can utilise a slab thickness much greater than 100mm as the surface area for heat transfer is effectively doubled.

- In addition to allowing heat flow to and from the top of the floor slab, underfloor ventilation can also be configured to create turbulent air in the floor void, which enhances the cooling rate and allows heat to penetrate further into the top surface.

- Profiled soffits (e.g. coffered, troughed, wave form, etc), provide an increased surface area which improves convective heat transfer, increasing the overall cooling performance.

Taking account of the points above, buildings with exposed soffits and underfloor ventilation can often take advantage of the thermal mass available in concrete floor slabs of 250 mm or more.

Control - Night cooling should take maximum advantage of ambient conditions whilst avoiding overcooling, which will cause discomfort at the start of the day, and may result in the subsequent need to reheat the space. Mixed-mode systems should default to natural ventilation whenever possible so the energy consumed by running fans is minimised. To achieve these objectives a number of different control strategies, which vary in their approach can be used. However, Research by BSRIA[5] in the UK has shown that a complex control strategy is often unnecessary. The careful selection of the control set-point to initiate night cooling was, however, identified as being of great importance. As a result of the monitoring, and further research using computer simulations, BSRIA recommend the following night cooling strategy for the UK (set points may need changing for other climates):

1. Select one, or a combination of the following criteria, to initiate night cooling:
    - Peak zone temperature (any zone) >23°C
    - Average daytime zone temperature (any zone) >22°C
    - Average afternoon outside air temperature >20°C
    - Slab temperature >23°C

2. Night cooling should continue providing the following conditions are satisfied:
    - Zone temperature (any zone) > outside air temperature (plus an allowance for fan pick-up if mechanical ventilation is used)
    - Zone temperature (any zone) > heating set point
    - Minimum outside air temperature > 12°C

3. Night cooling should be enabled (potentially available):
    - Days: seven days per week
    - Time: entire non-occupied period
    - Lag: if night cooling is operated for five nights or more, it should be continued for a further two nights after the external air temperature falls below the control set-point

Daylighting - Exposed concrete soffits can help to provide good daylight penetration when designed in unison with the façade. The objective is to maximise the daylight within the space without causing excessive glare and solar gains. A high window head allows light to be reflected off the soffit and travel well beyond the perimeter zone. The use of profiled soffits (e.g. coffered) running parallel to the path of daylight can enhance daylight penetration. Slabs can also be angled slightly upwards towards atria or windows to improve performance. In addition to aiding daylighting, profiled slabs can provide a positive visual aspect to the lighting design by creating areas of contrast which help to define room geometries. Ideally, a high surface reflectance of at least 70–80% should be achieved, and a gloss factor of no more than 10% to prevent lamps from becoming visible. A simple painted finish using white emulsion is a particularly effective way to achieve this, and provides a cost-effective solution that has been widely used. Another option is to use white cement in the mix to provide a light surface finish that is largely maintenance free. The use of an unpainted soffit made with white cement requires a high standard of casting to achieve a consistent, fair-faced finish.

Shading - Internal blinds intercept and absorb solar radiation after it has entered the building and then reradiate a significant proportion of this into the room. Consequently, when used as the only means of shading, they generally provide insufficient attenuation of solar gain in passively cooled buildings. Ideally the main shading should be external to reduce this problem. Recent advances in glass technology have provided coatings that can distinguish between longer-wavelength solar heat and shorter wavelength visible light. This can be beneficial; however, given the large overlap in wavelength between the two, there is a limit to how far this technology can be used to limit heat gains. Horizontal overhangs and projections on south-facing facades work well in mid-summer, but unless they are practically deep, will be less effective in the spring and autumn when the sun is lower in the sky. To counter this and provide some glare control, a combination of fixed external shading in combination with some form of adjustable blind can provide a good overall solution.

Project planning - Traditional responsibilities and boundaries within the design team may be challenged in projects featuring a high thermal mass solution as the floor slabs shift from being a purely structural element to something that has implications for a range of design issues including aesthetics, lighting, acoustics and thermal performance.

An early appointment of the team is important if the outcome of a high thermal mass project is to be successful, and the agreed terms should ensure that:

- Additional duties relating to the passive cooling strategy are defined and recognised. For example, with high thermal mass projects there is more likely to be a requirement for a design assessment using Computational Fluid Dynamics (CFD), and for post-handover monitoring to enable fine-tuning of the completed building.

- There is a clear demarcation between the responsibilities of the architect relative to the building-services engineer; in high thermal mass building there is far more overlap between the roles of these parties and, hence, potential for confusion of responsibilities.

- The structural and building-services engineers' views are given equal weighting alongside the architect's on matters that will affect the eventual performance of the cooling solution. Opportunities for increasing the cooling output from the thermal mass may be lost where aesthetic considerations alone are given precedence.

It is essential where an option to use the thermal mass for cooling is being contemplated, that this forms an integral part of the brief, and key decisions regarding this certainly need to be taken before any significant architectural design work on the building is undertaken.

Illustrations on this page:
Lycée du Pic-Saint-Loup
(School of Pic-Saint-Loup)
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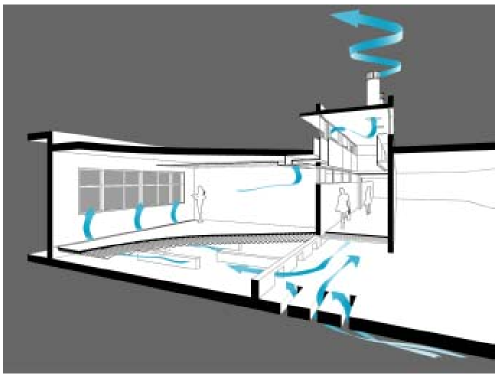
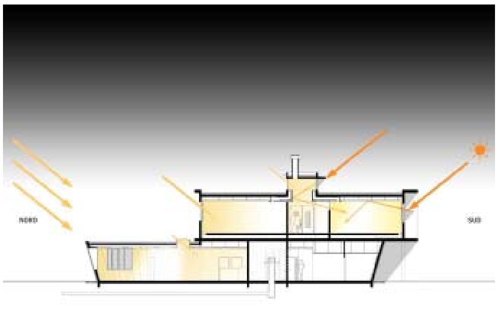
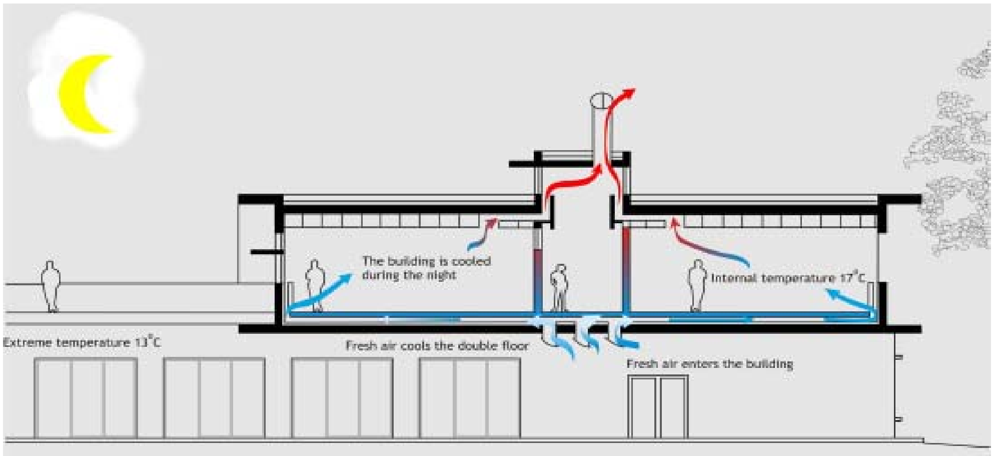
Project Manager: Serge Sanchis
Photos: © Abbadie

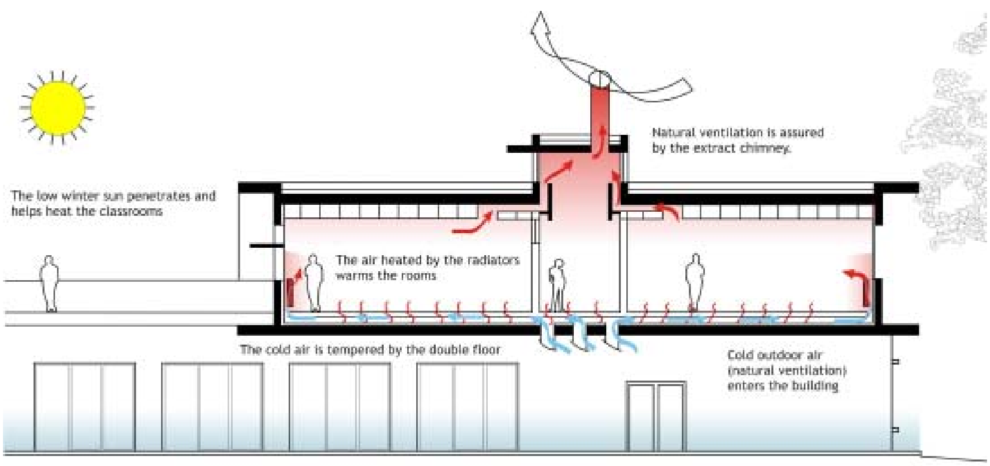




Natural lighting



Summer night

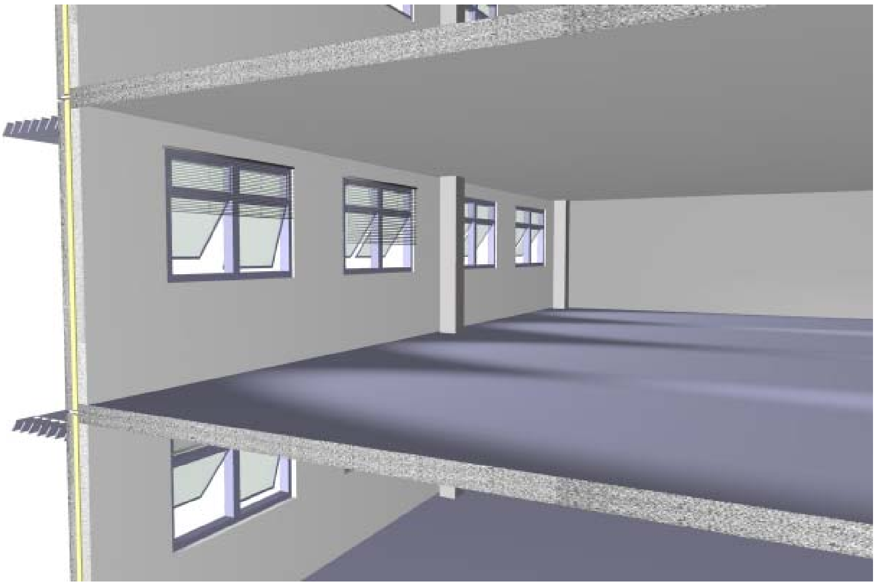


Winter Day

Slab options: Exposed slab with natural ventilation - Flat concrete slabs are quick and easy to construct and economical for spans up to about 9m (13m with post tensioning). They are also the simplest way of providing a high degree of thermal mass. When used in conjunction with natural ventilation from openable windows, the slab can provide around 15-20W/m^2 of cooling.

The increased surface area of profiled/ coffered slabs improves thermal performance. While this has little effect on radiant heat transfer, the increase in surface area improves convective heat transfer, which can be doubled in some instances[6]. The cooling capacity of a profiled slab is typically in the order of 20-25W/m^2. In addition to their aesthetic qualities, profiled slabs assist in maximising daylight penetration and provide improved acoustic control.

Formwork costs are generally higher, but pre-casting is an option, which brings with it the potential for savings in site time and the quality benefits that a more controlled casting environment can offer.



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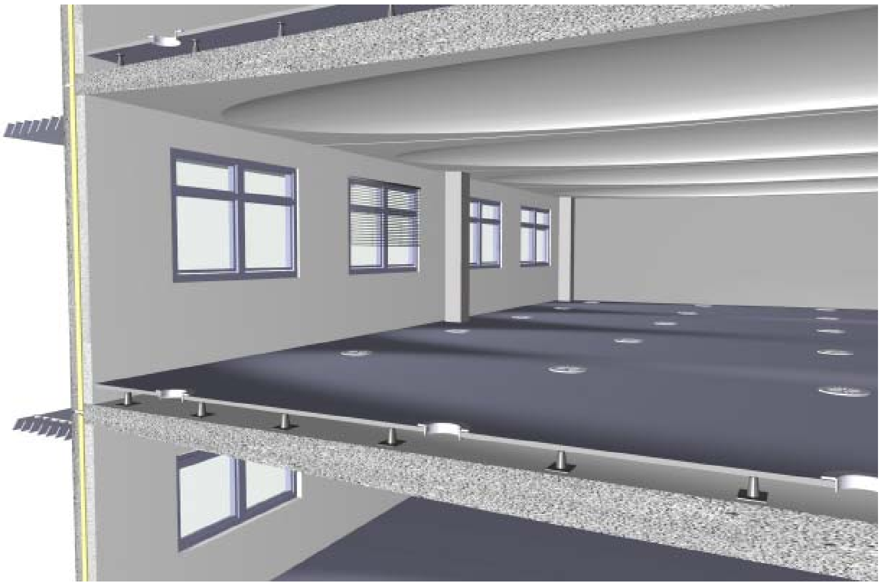
Slab options: Exposed slab with mechanical underfloor ventilation - Raised floors are generally considered essential for routing small power and communications in office buildings, and can also provide a useful means to provide ventilation, via floor outlets. This has the benefit of reducing ductwork and allowing outlets to be easily relocated to meet organisational changes. A further benefit of this technique is the direct contact between the air and the top of the slab, which allows utilisation of the thermal mass in the upper portion of the slab (see 'Optimal slab thickness'). If used in combination with a profiled soffit, which is not uncommon, the overall cooling capacity from the floor slabs will be in order of 25-35W/m^2.



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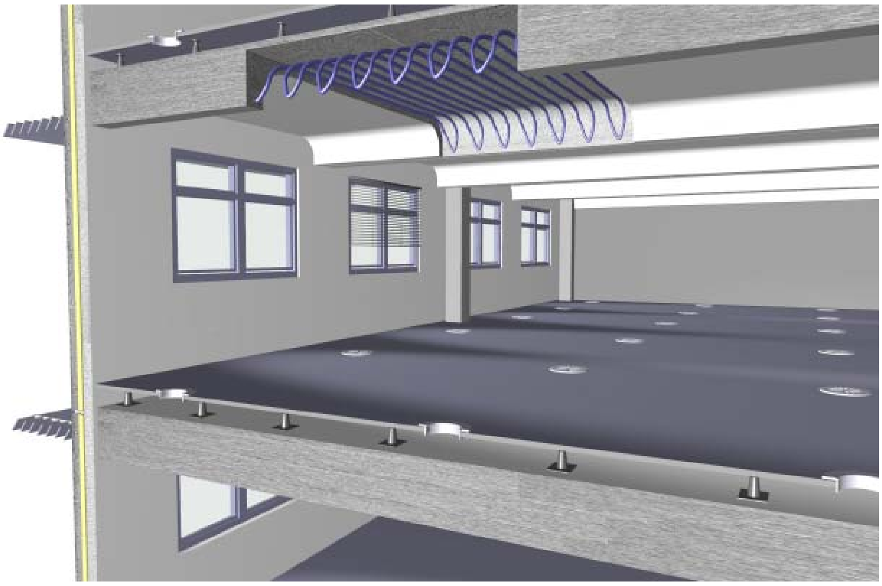
Slab Options: Exposed hollowcore slab with mechanical ventilation - Precast, hollowcore slabs with mechanical ventilation supplied via the cores, provide excellent heat transfer between the air and concrete, enabling a cooling capacity of up to 40W/m². Performance during the heating season is also excellent, making the use of hollow core slabs for heating and cooling an attractive year-round design option. The technique was originally developed in Sweden and is marketed under the brand name «Termodeck», and has been used in many hundreds of low energy buildings.

Illustration © The Concrete Centre

Slab Options: Exposed slab with water cooling/heating - The use of water rather than air to cool floor slabs enables higher cooling capacities to be achieved by significantly increasing the rate of heat transfer. As the uncertainties and limited duration of night-time ventilation do not apply, water cooled slabs provide a more predicable output that can, if necessary, be maintained 24 hours a day. The system typically comprises of polybutylene pipe embedded in the slab about 50mm below the surface, through which water is circulated at approximately 14-20°C during the summer and 25-40°C during the heating season. The technology is equally applicable to cast-in-situ and precast slabs, and can provide a cooling capacity of around 60-80W/m².

The speed of response using water cooling is relatively fast, taking around 3 minutes for a change in the flow temperature to have a discernible effect at the surface of the slab. This give a level of control not easily achieved in the other systems. In practical terms, this ensures a steady slab temperature can be maintained, preventing it from rising to a point where overheating might otherwise be experienced during peak conditions.

A number of options can be used to supply chilled water, including mechanical chilling, natural water sources, or a combination of the two. The relatively high chilled water temperature (required to avoid condensation forming) allows use of water from sources such as rivers, lakes and boreholes.



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Mechanical chilling can also be used where natural sources are not an option. Capital savings are possible with the chiller plant which can be relatively small as the thermal mass will reduce the peak cooling load (which is used to size the chiller).

Slab Options: Exposed slab with chilled beams - In recent years, the combination of chilled beams and exposed concrete soffits has become an increasingly popular solution in both new and retrofit projects. In particular, multi-service chilled beams have found favour with many architects and clients. This can be largely attributed to the simplification of ceiling located services by using what is essentially a packaged system that can, if required, completely avoid the need for a suspended ceiling. Another key feature of chilled beams is their ability to work with the fabric of the building by supplementing the passive cooling from thermal mass. The maximum cooling output from chilled beams is in the order of 100-160W/m^2, with additional cooling provided by the slab's thermal mass and potentially from the ventilation system as well if the air is conditioned. Ventilation is essentially a separate provision, generally via either natural ventilation or a mixed-mode underfloor system. The beams typically operate with chilled or cooled water between 14°C and 18°C, offering the potential to utilise water from sources such as lakes and boreholes. Passive cooling from the thermal mass is provided in the usual way, with the chilled beams operating during the daytime to boost the overall cooling capacity. In some installations, especially those using natural water sources, it may be advantageous to also operate the beams at night during hot weather to supplement night cooling from ventilation.

Illustration © The Concrete Centre

Footnotes

1 *Thermal mass for Housing, The Concrete Centre, 2008*
2 *Edwards B. Rough Guide to Sustainability, 2nd Edition, RIBA Enterprises, 2005.*
3 *Balaras C. Passive Cooling of Buildings, 1997.*
4 *Planning for Passive Solar design, Energy Efficiency Best Practice Programme, department of Trade and Industry, produced by BRECSU/BRE.*
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6 *Barnard N, Concannon P, Jaunzens D, Modelling the Performance of Thermal Mass, Information Paper IP6/01, BRE, 2001.*

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