The **Concrete** Centre™

Thermal Mass

A CONCRETE SOLUTION FOR THE CHANGING CLIMATE

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An internal view of the Powergen offices
showing the exposed concrete soffits (Architect: Bennetts Associates).
© Peter Cook/View

Front cover (left to right):

RSPCA Headquarters, courtesy of whitbybird
Photography: Jaap Oepkes

Canon Headquarters, courtesy of the Concrete Society

INTRODUCTION

Our climate is changing. The ongoing debates are only focused on the cause and the likely extent of the change. As temperatures increase there will be a growing need to control internal building temperatures. Concrete with its high thermal mass provides a sustainable solution.

Increasing energy prices, changes to the Building Regulations and growing concerns over climate change are continuing to put pressure on designers, developers and building occupiers to reconsider the use of energy intensive air-conditioning. For many building types, a cost-effective and more sustainable option is the combination of high thermal mass and night cooling, a solution that is especially effective where steps are taken to minimise heat gains. Both now and in the future this technology, also known as fabric energy storage (FES), has an important role to play in providing a passive, more sustainable alternative to air-conditioning.

Most FES systems centre on the building's thermal mass, provided by exposed concrete floor slabs. The slabs absorb internal heat gains, helping to prevent overheating and ensuring a more stable internal temperature. Night cooling purges the accumulated heat from the slab, preparing it for the next day.

In buildings where mechanical air-conditioning cannot be avoided FES can still provide a means of significantly reducing the energy required to operate the plant and the associated carbon dioxide (CO_2) emissions. For many buildings a basic FES system using natural ventilation is all that is required to provide satisfactory internal conditions and prevent overheating problems. More demanding applications may require the increased cooling capacity provided by supplementing natural ventilation with mechanical ventilation, typically in the form of a mixed-mode system. Alternatively, floor slabs can be water-cooled to provide maximum FES performance.

This publication outlines the application of these techniques using cast in situ and precast floor slabs in non-domestic buildings, it provides general information on FES design issues and brings together rules of thumb. The guide is not intended to be exhaustive and a range of referenced sources are given for further reading.

For clarity, degrees celsius (°C) have been used for all references to temperature throughout this publication.

Toyota GB Headquarters: interior (left), precast concrete soffit unit (right), courtesy of Trent Concrete (Architect: Sheppard Robson).

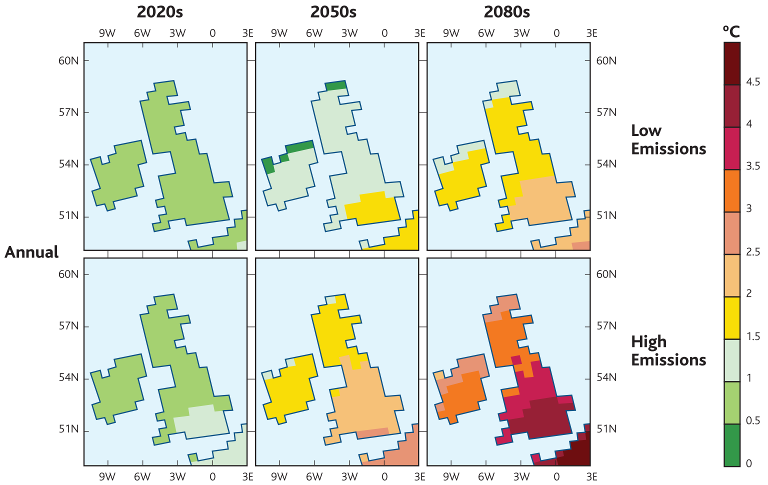
We need to design and build structures now that can cope with future climate predictions.

CLIMATE CHANGE AND THE TURN TO THERMAL MASS

Facing both rising temperatures and the subsequent demand to provide comfortable working and living conditions without using air-conditioning, more and more design teams are incorporating the use of thermal mass into their structures.

According to the UK Climate Impacts Programme (UKCIP), UK annual temperatures could have increased by between 2°C and 3.5°C by the 2080s (based on the medium-high scenario[UKCIP02]). Summer increases will be roughly double those seen in the winter, giving an increase of approximately 6°C for the average daily maximum temperature during August in the South East of England.

CHANGE IN AVERAGE ANNUAL TEMPERATURE
(UKCIP02 Briefing report, April 2002)



However, overheating is already a significant issue for a number of buildings in the UK. New research [1] shows many existing offices and dwellings will experience overheating, especially towards the middle of this century and beyond. A typical naturally ventilated office built in the 1960s is likely to exceed 28°C for around 15% of its occupied period. Current advice is that 28°C should not be exceeded for more than1% of the occupied period, to maintain an adequate level of comfort [2].

Adaptive measures to help mitigate effects of climate change include external shading, reducing internal heat gains and combining thermal mass with night cooling - FES. When used alongside heat reduction measures, FES provides an effective means of lowering internal temperatures, helping reduce demand for air-conditioning.

When considering sustainability issues, it is the energy and CO_2 emissions associated with the operation of buildings that are of the greatest significance and not the choice of materials used in their construction. Over the life of a concrete frame building, the reduction in CO_2 emissions by using FES to avoid or minimise air-conditioning can be several times greater than the embodied CO_2 in the concrete floor slabs and other building elements. The precise ratio is determined by a wide range of factors, such as the choice between natural and mechanical ventilation. Another factor is climate change itself; as the century progresses, the ratio between the heating and cooling energy used in buildings will shift, with the expectation that the cooling energy used by air-conditioning will increase year on year. Consequently the potential for FES to save energy and cut CO_2 emissions is likely to grow at a similar pace.

FABRIC ENERGY STORAGE (FES) PERFORMANCE

THE BASIC OPERATING PRINCIPLE

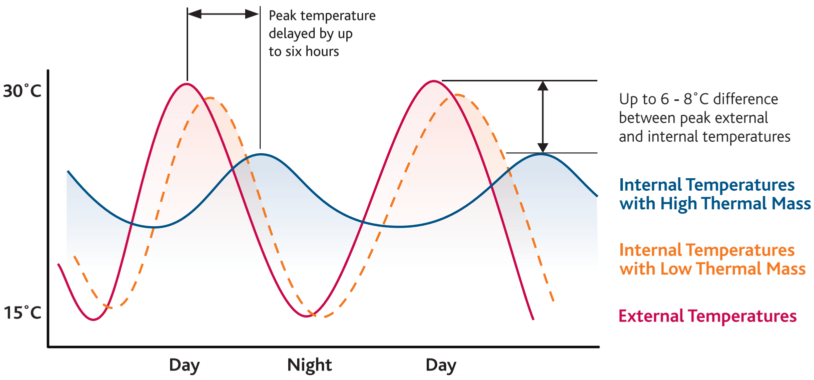
The dynamic thermal response of high thermal mass buildings with exposed concrete is characterised by a slow response to changes in ambient conditions and the ability to reduce peak temperatures. This is particularly beneficial during the summer, when the concrete absorbs internal heat gains during the day, helping to prevent overheating.

In addition to reducing peak internal temperatures, a high thermal mass building can also delay its onset by up to six hours [3]. In an office environment this will typically occur in the late afternoon, or the evening after the occupants have left. At this point the FES cycle is reversed, with solar gains greatly diminished and little heat generated by occupants, equipment and lighting. As the evening progresses the external air temperature drops, making night ventilation an effective means of removing accumulated heat from the concrete and lowering the temperature in preparation for the next day. The UK variation in diurnal temperature rarely drops below 5°C, making night cooling relatively effective. Water can also be used to cool the slabs as an alternative to, or addition to, night ventilation.*

Concrete's ability to absorb heat and provide a cooling effect comes from the difference between the surface temperature and that of the internal air. Consequently, the greatest cooling capacity is provided when the internal temperature peaks. Therefore, to some extent a variable internal temperature is a prerequisite in FES systems. However, to maintain comfortable conditions and limit overheating, peak temperatures should ideally not exceed 25°C for more than 5% of the occupied period and 28°C for not more than 1% [2].

Resultant temperature is an important measure of FES. It takes account of radiant and air temperature, providing a more accurate indication of comfort than air temperature alone. The relatively stable radiant temperature provided by the thermal mass in concrete is a significant factor in maintaining comfortable conditions. It enables higher air temperatures to be tolerated than in lighter-weight buildings, which are subject to higher radiant temperatures resulting from warmer internal surfaces.

STABILISING EFFECT OF THERMAL MASS ON INTERNAL TEMPERATURE



STRUCTURAL WEIGHT AND THERMAL MASS

False ceilings, raised floors and carpets in buildings, particularly offices, effectively isolates the thermal mass of the concrete structure underfoot and overhead. They can severely limit the concrete's ability to absorb and release heat within the occupied space. Buildings like this can be described as thermally lightweight, even though they may be structurally heavyweight. Consequently, it does not necessarily follow that a structurally heavyweight building will automatically provide high thermal mass; this depends on the extent to which the structural elements can thermally interact with the occupied space, a relationship that is known as thermal linking.

In existing buildings thermal linking can often be improved during refurbishment by removing wall and floor coverings. Removing false ceilings or introducing a permeable ceiling will unlock the thermal mass in the slab.** Hard floorings such as tile, work well from a thermal perspective, but are rarely practical. Raised floors prevent radiant heat transfer with the concrete slab below, but still allow good convective heat transfer when used as a plenum for underfloor ventilation.***

Precast soffit unit improves energy efficiency and air quality.

Atrium, showing exposed concrete frame.

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* See page 20
** See page 16
*** See page 14

When designed appropriately, thermal mass will help to reduce summer and winter energy demands.

VENTILATION RATES

Ventilation for night cooling requires an air change rate in the order of 2 to 5 per hour [4]. The optimum rate will depend on each building's specific characteristics. Elevated air change rates will improve the cooling rate to a limited extent, but the two are not directly proportional. This is because the cooling rate is also affected by the length of time the air is in contact with the slab. High air change rates results in less contact time.

To allow sufficient time for night cooling, the occupancy period should ideally not be more than 10 hours [5]. Buildings occupied for longer periods may not be suitable for FES with natural or mechanical ventilation, requiring instead water-cooled slabs which enable heat removal at a faster rate.

COOLING LOADS

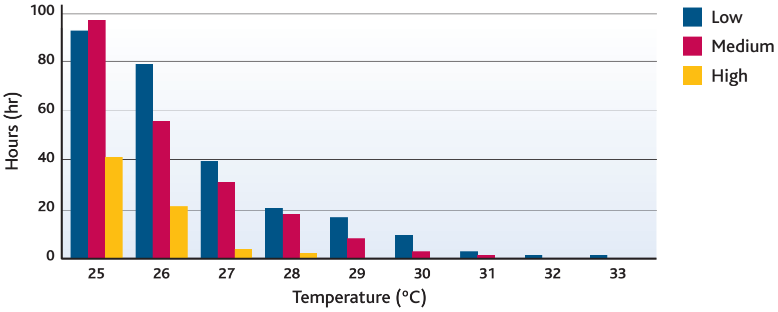
A typical naturally ventilated building, without an FES system, will be able to offset heat gains of approximately 25 W/m^2 from solar, lighting, equipment and occupants [6]. The addition of an exposed concrete soffit, in conjunction with an appropriate night cooling strategy and steps to minimise heat gains, will give an additional cooling capacity of approximately 15-20 W/m^2, providing the diurnal temperature swing is at least 5°C [7] (which occurs for over 90% of the summer in the south-east of England [8]). Therefore, the total heat gain that can be offset by a naturally ventilated building with a simple FES system is approximately 40 W/m^2. Cooling capacities of other FES techniques ranging from 10-80 W/m^2 are detailed later in this publication.*

INTERNAL TEMPERATURES

Typical summertime benefits of introducing a night cooling strategy in a heavyweight building can result in a 3°C reduction in peak temperatures [9]. Internal temperatures can be held up to 6-8°C below peak external summertime temperatures, if internal heat gains are kept reasonably low and good solar shading is provided [7].

The graph below illustrates the extent to which thermal mass can reduce peak internal temperature experienced in an office building. Results show that for around 20 hours a year the low and medium thermal mass constructions exceed 28°C, the generally accepted upper comfort limit (that should not be exceeded for more than 1% of the occupied period [2]). It is based on the results of a thermal modelling investigation carried out by BRE [9] on a naturally ventilated, open plan office derived from a model described in ECON 19 [10], using weather data from 1994 for Heathrow/Bracknell. Variations in thermal mass were achieved in the following way:

1. **Low thermal mass:** false ceiling, false floor, lightweight walls and partitions
2. **Medium thermal mass:** exposed lightweight concrete soffits, false floor, mediumweight walls and partitions
3. **High thermal mass:** exposed heavyweight concrete soffits, false floor, heavyweight walls and partitions



Comparison of hours experienced at varying internal temperatures for a naturally ventilated office with high, medium and low thermal mass, located in the London area.

Vodafone Headquarters, a high thermal mass building benefiting from exposed concrete slabs, natural ventilation and good external shading (Architect: Fletcher Priest Architects).
© Chris Gascoigne/View

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* See pages 12-23

HEATING ENERGY

The heating energy used by high thermal mass buildings is a complex issue that can be affected by the following factors:

- Level of insulation and airtightness
- Heating strategy – continuous or intermittent
- FES control strategy*
- Use of mechanical ventilation with heat recovery
- Building design – whether the façade and positioning of the thermal mass will capture solar gains during the winter as well as providing passive cooling in summer
- Effectiveness of the occupant's control of their environment

In the UK, high thermal mass buildings have traditionally tended to use slightly more heating energy during the winter than lighter-weight structures. This can be attributed to infiltration and fabric heat loss cooling the structure at night when the heating is off, resulting in a longer pre-heat period in the morning.

In new buildings this issue is greatly diminished due to the ongoing tightening of insulation and airtightness standards in the Building Regulations. The use of mechanical ventilation can further reduce the heating energy required, by providing close control of ventilation rates and enabling heat recovery. The effect of using continuous instead of intermittent heating can also be advantageous; as insulation and airtightness standards continue to improve, low levels of continuous heating may become the preferred heating strategy, especially in buildings with a high thermal capacity [11].

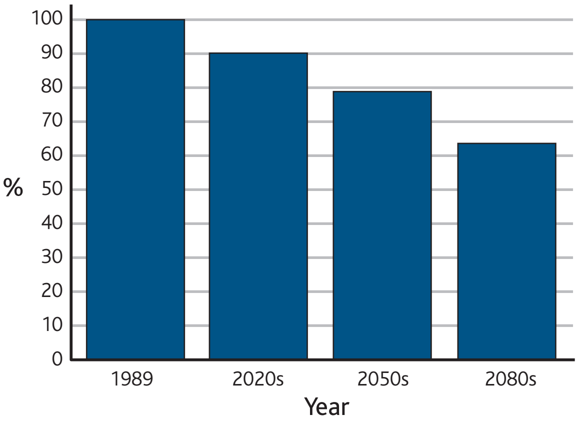
Climate change will have a positive impact on heating energy, with new research [1] showing that by 2080 energy levels may well fall to about 60% of 1989 levels for the London area, and 70% for Edinburgh, due to increased winter time temperatures.

THERMAL MASS IN WINTER

The benefits of FES do not have to be limited to the summer months; buildings can be designed to capture solar gains during the winter, storing them using thermal mass. This technique has been used to good effect at the BEDZED housing development in South London, where it is estimated that heating energy usage is reduced by up to 30%.

Excess heat can also be captured from occupants, lighting, computers and other equipment. The stored heat is slowly released later in the day, helping to keep the building warm and reduce heating costs. Taking advantage of the winter sun requires large areas of south facing glazing. Radiant heat from a low winter sun is able to pass under external shading devices, which block the sun during the summer. This technique is beyond the scope of this publication but further reading is available [12,13].

CHANGE IN HEATING ENERGY REQUIREMENT FOR THE LONDON AREA, AS A PERCENTAGE OF 1980s USAGE [1]



BEDZED housing development, South London showing sunspaces (Architect: Bill Dunster Architects).

Interior of a flat in the BEDZED development
Photography: Linda Hancock.

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* See page 11

> The combination of exposed soffits and underfloor ventilation is capable of exploiting the thermal mass in slabs of 250 mm or more.

Canon Headquarters showing coffered concrete slabs which increase the surface area for improved FES performance. Courtesy of the Concrete Society (Architect: David Richmond & Partners).

OPTIMAL SLAB THICKNESS

Thermal mass can be provided by all of a building's structural elements, including walls, frame and floors. Even furniture can, to a limited extent, provide some reduction in heat gains. However, concrete slabs provide the bulk of the thermal mass in FES systems. The thickness of slabs needed for optimal performance depends on how it is used and the system selected.

Determining factors for slab thickness are described below:

1. It is generally accepted that in naturally ventilated buildings with exposed concrete soffits and insulated floors (no thermal linking), a concrete slab approximately 100 mm thick will provide a sufficient amount of thermal mass for a 24 hour heating and cooling cycle (Fig 1).

2. FES performance based on a simple 24 hour heating/cooling cycle requires less thermal mass than for a longer cycle, such as an extended period of warm weather. Therefore, slabs with the sufficient thickness for the 24 hour cycle (approximately 100 mm) will not provide sufficient thermal mass to prevent overheating during prolonged warm summer temperatures (Fig 2).

3. A slab with thermal linking on both sides, e.g. exposed soffit and underfloor ventilation, can make use of twice the slab thickness than is required for systems where only the soffit is exposed.

4. Underfloor ventilation or other means of increasing the convective heat transfer coefficient, will increase the rate at which heat flows in and out of the slab. This enhances the cooling capacity, needing a greater slab thickness for optimal performance.

5. Profiled slabs (e.g. coffered, troughed, wave form, etc), provide an increased surface area which enhances convective heat transfer, improving FES performance.

6. Taking account of points 2, 3 and 4, a building with exposed soffits and underfloor ventilation (providing enhanced convective heat transfer) should be capable of exploiting the thermal mass available in concrete floor slabs of 250 mm or more (Fig 3).

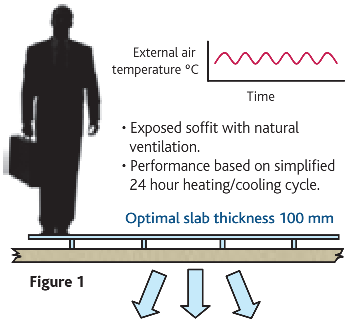


Figure 1

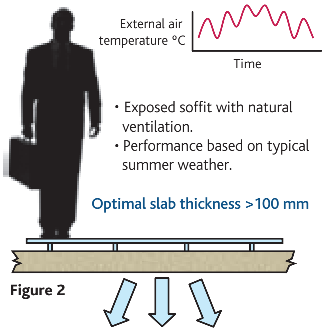


Figure 2

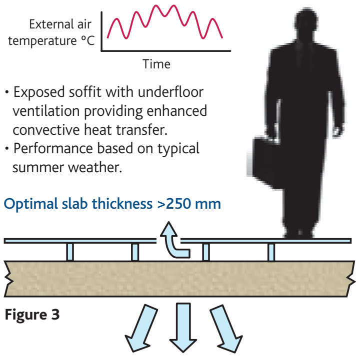


Figure 3

ADMITTANCE – AN INDICATOR OF FES PERFORMANCE

A measure of comparative FES performance in different constructions is provided by their admittance value.

Admittance only describes the ability of a material or construction to exchange heat with the environment when subjected to a simple cyclic variation in temperature (typically 24 hours for buildings). It is measured in W/m^2 K, where temperature is the difference between the mean value and actual value within the space at a specific point in time.

Key variables that determine admittance are thermal capacity, conductivity, density and surface resistance. However, the admittance for structures with a high thermal mass is ultimately limited by the rate of heat transfer between the structure's surface and the surrounding air. This places an upper admittance limit of 8.3 W/m^2 K [4] on basic FES systems dependent on natural ventilation. This figure may be increased by mechanical ventilation, used to provide turbulence at the air/structure interface, resulting in greater convective heat transfer.* During the early stages of design, admittance can provide a useful means of assessing the likely performance of different constructions. The table below provides some comparative values for different constructions. A more accurate indication of FES performance requires detailed thermal modelling, taking into account real weather patterns and the more varied nature of heat flow to and from the building fabric.

MODELLING THE PERFORMANCE OF FES SYSTEMS

Due to the dynamic nature of the internal and external environment assessing the effectiveness of an FES design is not straightforward. Software that uses the admittance method to assess summertime performance is limited by the simple sinusoidal temperature variation upon which it is based. Consequently, to provide anything other than a basic evaluation requires dynamic thermal simulation software, using finite difference algorithms. This models the response of a building to real weather data more accurately. It analyses performance under a range of conditions including extended periods of hot weather.

Computational fluid dynamics (CFD) modelling can be used to provide highly detailed analysis of internal spaces and a graphical assessment of air movement and temperature. It is particularly helpful for analysing spaces such as atriums for airflow patterns and localised temperatures under peak conditions.

An experienced operator able to make qualitative judgments regarding the assumptions and simplifications that are invariably required when inputting data, is essential to get meaningful answers from thermal modelling tools. Many larger building services design consultancies employ a dedicated team of modelling engineers with this level of expertise. The cost of carrying out a detailed assessment of an FES design can be worthwhile, given the relatively fine line that can exist between maintaining acceptable conditions and the risk of overheating. Recommended further reading on this topic is given [9,15].

EXAMPLES OF ADMITTANCE FOR DIFFERENT BUILDING CONSTRUCTIONS

Higher values indicate a better ability to exchange heat with the environment, and provide good FES performance.
(Unless otherwise indicated, data is from CIBSE Guide A – Environmental Design, Tables 3.54 & 3.56 [2])
Note: Improvements to the level of insulation specified in these constructions to meet current Building Regulations will have little impact on the values of admittance shown.

Wall Constructions:	**Admittance W/m^2 K**
Precast concrete sandwich panel wall: 19 mm render, 80 mm dense concrete, 50 mm EPS insulation, 100 mm dense concrete, 13 mm dense plaster.	5.48
Brick/dense concrete block cavity walls: 105 mm brick, EPS insulation, 100 mm dense concrete block, 13 mm dense plaster.	5.75
Brick & block cavity wall: 105 mm brick, 25 mm airspace, 25 mm EPS insulation, 100 mm lightweight aggregate concrete block, 13 mm dense plaster.	2.95
Timber frame wall: 105 mm brick, 50 mm airspace, 19 mm plywood sheathing, 140 mm studding, 140 mm mineral fibre insulation between studs, 13 mm plasterboard.	0.86
Internal Partitions:	
Block partition: 13 mm lightweight plaster, 100 mm lightweight concrete block, 13 mm lightweight plaster.	2.09
Timber studding: 12 mm plasterboard, timber studding, 12 mm plasterboard.	0.69
Internal Floor/Ceiling Constructions:	
Dense cast concrete: 100 mm dense cast concrete, no plaster [14].	6.57
Cast concrete: 50 mm screed, 150 mm cast concrete, 13 mm dense plaster.	5.09
Timber flooring: 19 mm timber flooring or chipboard on 100 mm joists, 12 mm plasterboard ceiling.	1.89

* See pages 14 and 18

Natural ventilation provides the simplest method of night cooling in buildings with modest cooling requirements.

PASSIVE FES - NATURAL VENTILATION

Natural ventilation provides the simplest method for night cooling. However, it is particularly dependent on the external temperature and wind speed/direction. A stack effect created as part of a natural, secure and weatherproof ventilation system can mitigate the effects of a still summer night, but this solution requires an atrium ventilation chimney or other structural device.

A mixed-mode system is often used to provide more predictable cooling performance whilst retaining the benefits of natural ventilation. This combines natural with mechanical ventilation to ensure adequate air flow under all conditions.*

For buildings with a modest cooling requirement, natural ventilation alone can provide a range of benefits:

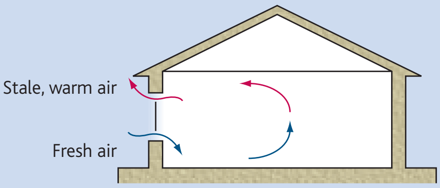
- Very simple operation
- No energy requirement or CO_2 emissions
- Occupants are empowered to take control of their environment. This has been shown to result in greater tolerance of higher internal temperatures [16]
- Building space is maximised through avoidance of mechanical plant and distribution systems
- Low capital costs (although high quality windows and shading are important)
- Minimal operating and maintenance costs

Effective control of natural ventilation requires a well designed and user friendly window system to take maximum advantage of the prevailing conditions. Solar shading, effective in minimising solar gains is equally important. During the summer months, heat gains offset by passive FES systems are relatively modest, making the performance of windows and shading a significant determinant in the systems overall success. Consequently, they are likely to represent a significant component in the overall project costs.

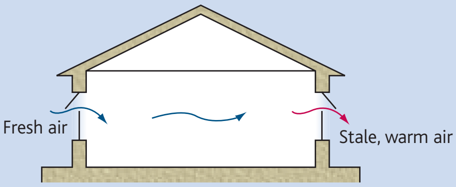
The effectiveness of building users in controlling their own environment is important, especially the manual switching off of equipment and lighting when not in use, along with the appropriate use of windows and shading. Users need to understand the basic design intent and the extent to which they are responsible for their own comfort – something that will be new to individuals more used to a fully air-conditioned environment.

Where heat gains exceed 30 W/m^2, and the plan depth is greater than 7 m for single sided ventilation or 12 m for cross ventilation, natural ventilation is unlikely to be suitable on its own and will require an active system in the form of a mixed-mode or full mechanical system [17]. Recommended further reading on natural ventilation is given [18,19].

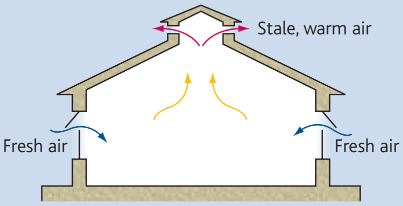
Basic systems/techniques for providing natural ventilation.



Single Sided Ventilation



Cross Ventilation



Stack Ventilation on a Still Day

* See page 10

WINDOW CONTROL

Automating window opening and closure can help minimise design risk associated with occupant control, but can prevent the psychological benefits provided by empowering individuals with some control over their environment. A popular technique which avoids this problem is a combination of manual and automatic control. With this approach high level fanlight windows are operated by powered actuators linked to a building management system (BMS), which controls their opening in response to temperature, wind speed and direction, etc. The occupants control the low level windows which, for much of the summer, they are free to open or close as they please. At the end of the day the low level windows are closed, whilst the BMS continues to control the fanlight windows for optimal night cooling of the building fabric. During periods when the external temperature is too high for beneficial ventilation, email can be used to advise occupants in perimeter locations to close their windows. Alternatively a BMS controlled traffic light system, provides a visual guide to the most appropriate window setting for the conditions. This approach has been used to good effect at the BT Brentwood Building [20].

ATRIUMS

Atriums provide a pleasant working environment, and increase social interaction between floors. They can also greatly assist air flow, especially on hot, still nights when there is not enough wind pressure to move air through the building. Fresh air enters through perimeter windows and moves across the occupied space into the atrium. Increased buoyancy from the heat gains provides a stack effect, allowing the air to be exhausted at a high level through windows with powered actuators. This process may also be assisted by wind pressure, with the balance of driving forces being largely dependent on ambient conditions.

Central atriums are a key feature in many owner-occupied high thermal mass office buildings. The atrium works in unison with narrow floor plates and an open balcony arrangement, to provide an unobstructed path into the atrium. Natural ventilation in these buildings is often supplemented by a mechanical underfloor supply to provide a mixed-mode solution.

WIND /STACK VENTILATORS

Where atriums and openable windows are not an option, combined stack and wind ventilators may provide an effective alternative. These contain a volume control damper that can be programmed to fully open at night and close again at a predetermined time, or when a lower temperature limit is reached to avoid overcooling [19].

VENTILATOR PANELS

Another option is to use bottom hung ventilator panels located below the perimeter windows. Perforated external louvres provide weather protection, while a mesh screen provides security, allowing them to be left open overnight. A short case study describing the use of ventilator panels is provided in BRE Information Paper 4/98: 'Night Ventilation for Cooling Office Buildings' [8].

Atrium in the Faculty of Divinity, Cambridge, courtesy of whitbybird (Architect: Edward Cullinan Architects). Photography: Peter Durant

Example of a wind ventilator that catches the prevailing wind for use as natural ventilation, courtesy of Monodraught.

Mixed-mode ventilation offers many of the benefits of natural ventilation, whilst providing greater control of night cooling.

ACTIVE FES – MIXED-MODE VENTILATION

The term mixed-mode typically describes a system that combines natural and mechanical ventilation that is widely used in the UK. It provides many of the advantages of natural ventilation, as well as, other benefits particularly relevant to FES. These can be summarised as follows:

- Greater control over internal conditions
- Secure and weather-proof night ventilation
- Improved ventilation on still nights, especially where stack ventilation is not possible
- The ability to offset higher heat gains
- Greater building flexibility to cope with changes of use, occupant density, internal loads, etc.
- The option to enhance system performance in the future, through the addition of a cooling coil within the air handling unit(s) supplied by a chiller, evaporative cooler, heat pump, borehole/lake, etc.
- Draught-free winter ventilation, with the benefit of heat recovery by virtue of the mechanical air handling system
- The ability to ventilate areas not suited to natural ventilation due to nearby external noise or pollution, or excessive distance from a window

For most active FES systems a mixed-mode approach is generally preferred to full time mechanical ventilation, which affords building occupants very little control over their environment. Natural ventilation also realises the benefits of free cooling, i.e. ventilation without the need to operate fans (fans account for a significant proportion of the energy used in mechanically ventilated buildings).

The combination of centralised plant supplying an underfloor ventilation system is a particularly effective format in mixed-mode FES systems.* This solution provides good convective heat transfer with the top of the slab, enabling thermal linking on both sides in buildings with exposed soffits. Centralised air handling plant enables the heat lost by ventilation during the winter to be minimised by incorporating a heat recovery device such as a cross-flow heat exchanger, designed to recover heat from exhaust air to pre-heat incoming fresh air. During summer nights, a damper controlled bypass prevents the heat recovery device from warming the incoming fresh air. On very hot summer days, the incoming fresh air can be pre-cooled at times when the exhaust air is at a lower temperature. The effectiveness of pre-cooling can be enhanced through the addition of evaporative cooling of the exhaust air before it passes through the heat recovery device. This cools the fresh air, without increasing its moisture content, and depending on the ambient and internal conditions, can lower the supply temperature by several degrees. Recommended further reading on this topic is given [21].

Formwork for coffered slabs at the RSPCA Headquarters, West Sussex (Architect: Miller Hughes Associates).

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* See page 14

CONTROL OF NIGHT COOLING

Night cooling should take maximum advantage of ambient conditions whilst avoiding overcooling, which will result in uncomfortable conditions 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 and complexity can be used. The relative attributes of these control strategies have been investigated by the Building Services Research and Information Association (BSRIA), which undertook site monitoring of four high thermal mass buildings constructed in the 1990s. Each employed a different night cooling control strategy as detailed in the study [7]. The buildings featured in the study were:

- Inland Revenue Building, Durrington
- Inland Revenue Buildings B and F, Nottingham
- Ionica Building, Cambridge
- Powergen Headquarters, Coventry

BSRIA's key conclusion was that a complex control strategy is not necessary to maintain comfortable conditions and achieve energy savings in systems with mechanical ventilation. 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 recommended the following night cooling strategy [7].

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

The Ionica building - a high thermal mass building monitored in the BSRIA study (Architect: RH Partnerships).

A detail of the concrete frame at No 2 Leeds City office park which used a mixed-mode ventilation system, courtesy of Foggo Associates.

Cast in situ and precast slabs allow a more integrated approach to design, helping to fulfil structural, thermal and aesthetic requirements in a single element.

Jubilee Library, Brighton. A high thermal mass building benefiting from exposed in situ concrete column 'trees' that branch out to form the library floor. Outer office spaces utilise precast hollowcore concrete floors (not shown) (Architect: Bennetts Associates).

THERMAL MASS WITH PRECAST AND CAST IN SITU FLOOR SLABS

Both the structural weight and large surface area provided by floor slabs is central to the design of most FES systems. The high thermal mass of cast in situ and precast slabs are particularly effective, as they are, typically 200-400 mm thick. Use of a high quality finish allows the soffits to be exposed. Additionally, the ability to create a profiled finish can further enhance the overall appearance, whilst also providing a useful increase to the heat transfer area.

Cast in situ and precast slabs should be regarded as much more than simply a structural component. They allow a more integrated approach to design, helping to fulfil structural and aesthetic requirements in a single element, while also assisting in meeting acoustic and daylighting needs. A profiled soffit with a light coloured finish helps to maximise daylight penetration, while the mass of the slab minimises the transmission of structure-borne sound between floors.

Avoiding suspended ceilings enables much simpler building services installations, with a greater reliance on the structural form to provide a comfortable environment. This can provide significant financial savings, which can more than offset any additional cost of achieving the required soffit finish [22].

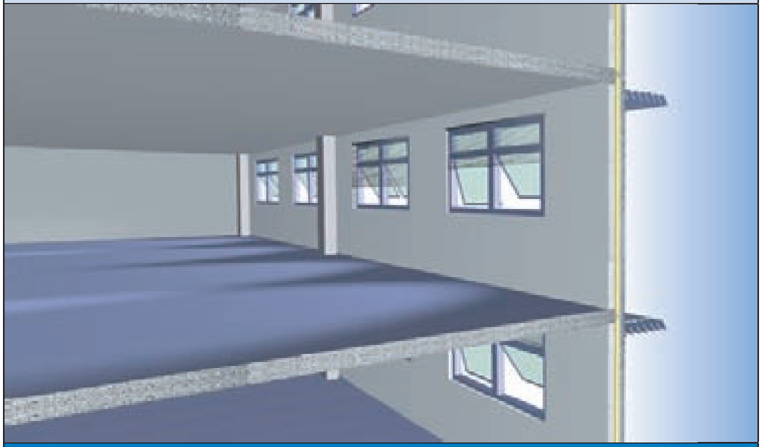
A further benefit of precast and cast in situ floor slabs is the range of FES design options that they allow. The following pages outline the generic options, and provide an indication of their comparative cooling performance and key attributes. Variations on the systems described can be used to provide bespoke solutions to meet specific project requirements, making FES a relatively flexible approach to passive and mixed-mode cooling. This is especially true when it comes to enhancing the cooling performance in mixed-mode systems. This can be achieved by the addition of a conventional chiller, but is equally possible with more passive techniques including evaporative cooling and the use of ground, or lake water to cool the supply air. Water sources can also be used to good effect with water-cooled slabs and chilled beams, which offer the highest cooling capacity of all the options featured.

OPTIONS FEATURED IN THIS SECTION

NATURAL VENTILATION, WITH EXPOSED SOFFITS

DESCRIPTION:

Flat or profiled floor slabs used in conjunction with natural ventilation. This may be wind driven, or a combination of wind and stack ventilation.



TYPICAL APPLICATIONS:

Offices, schools, universities

FES COOLING CAPACITY:

≈ 15-20 W/m^2 (flat slab)
≈ 20-25 W/m^2 (profiled)

KEY BENEFITS:

- Simple
- No fan energy
- Minimal maintenance
- Can be used in many existing buildings

KEY CONSIDERATIONS:

- Application limited to environments with low to moderate heat gains
- Performance is particularly weather dependent, and requires good occupant control
- External noise and security may preclude the use of openable windows
- Careful design and operation is required to ensure heating energy is minimised

CASE STUDIES:

- The Open University design studio, Milton Keynes [23]
- Park House, Teddington [24]
- Vodafone Headquarters, Newbury (Flat slabs and chilled beams) [25]

Flat slabs are quick and easy to construct and economical for spans up to 9 m (13 m with post tensioning). FES performance can be improved by using a profiled slab with coffers, troughs or a wave form finish. While this will have little effect on radiant heat transfer, the increase in surface area will improve the convective heat transfer, which can be doubled in some instances [9]. The cooling capacity of profiled slabs is in the order of 20-25 W/m^2.

In addition to their architecturally pleasing appearance, profiled slabs assist in maximising daylight penetration and provide improved acoustic control over a flat slab. Formwork costs are generally higher, but pre-manufacture is an option, which brings with it the potential for savings in site time and the quality benefits that a more controlled environment can bring to the manufacturing process.

High quality surface finish and detailing of exposed concrete

The use of underfloor ventilation helps to unlock the thermal mass in the upper part of the slab.

A perimeter office in Portcullis House, Westminster showing the precast wave form slabs (Architect: Michael Hopkins and Partners).

UNDERFLOOR VENTILATION WITH EXPOSED SOFFITS

DESCRIPTION:

The void created by a raised floor is used as a plenum for mechanical ventilation. Air enters the occupied space through floor diffusers. This solution is often used in conjunction with an exposed, profiled slab and as part of a mixed-mode system.

TYPICAL APPLICATIONS:

Offices, public and commercial buildings

FES COOLING CAPACITY:

≈ 25-35 W/m^2 with exposed, profiled soffits
≈ 20-30 W/m^2 with exposed, flat soffits

KEY BENEFITS:

- Enables thermal linking of the upper slab surface in buildings with raised floors
- Turbulent air in the floor void can provide good convective heat transfer, enabling higher cooling capacities than in naturally ventilated FES systems
- Good flexibility and the ability to accommodate changes in building use
- Can provide the benefits of mixed-mode ventilation

KEY CONSIDERATIONS:

- Space requirement for air handling plant
- Higher capital and operating costs than passive solutions (energy and maintenance)

CASE STUDIES:

- Powergen Headquarters, Coventry [26]
- Portcullis House, Westminster [27,28]
- Buildings P&T, Best Practice Programme Report 31 [4]

Raised floors are generally considered essential in routing small power and communications in commercial buildings. They are also becoming an increasingly popular way to supply fresh air, by using the void as a supply plenum, which has the advantage that the floor outlets can be readily moved to suit organisational requirements. A further benefit of this technique is the direct contact between the air and the slab, which helps to unlock the thermal mass in the upper slab section that would otherwise remain insulated by the raised floor tiles.

FES can be maximised by the combination of an underfloor ventilation supply and exposed soffits, which enable thermal linking of the slab from both sides. This effectively doubles the thickness of slab that can be used to provide thermal mass.* A further increase in slab thickness may be advantageous if the air travelling across the floor void is sufficiently turbulent to enhance the convective heat transfer at the surface. This can increase the admittance of the slab to a value of 10-20 W/m^2 K [29].

The optimal rate of heat transfer is dependent upon achieving a balance between the mean speed of the motion of the air and the time it spends in the floor void without incurring excessive fan gains. This requires the floor diffusers to be adequately balanced. One way to achieve this is to divide the floor void into approximately square compartments, each containing several diffusers. Each compartment is supplied via a damper linked to a central plenum duct running across the floor [30]. This will help ensure the air velocity and flow patterns within the void can be optimised for effective heat transfer.

Typically, the depth of raised floors used for ventilation is in the order of 300-450 mm [31], which is around 150-300 mm more than that required purely for structured cabling and other M&E installations. However, the absence of a suspended ceiling more than compensates for the additional floor depth, even where soffit mounted chilled beams are used to provide additional cooling.**

When considering mechanical ventilation as part of an FES design, the case for using underfloor ventilation is quite compelling for office-type environments, not least because exposed soffits leave few options for air distribution and the routing of other services. However, in addition to providing a means of ventilation and good thermal linking of the slab, other advantages are offered by an underfloor supply over ceiling-based air-conditioning systems, which include [20]:

- A reduction in the resources required to construct the building
- The ability to provide a higher proportion of fresh air to the occupants
- Lower maintenance
- Increased flexibility for future change of use
- Lower energy consumption
- Reduced carbon emissions

A model of a cross-section through the perimeter offices at Portcullis House, showing the ventilation supply plenum created by the raised floor, courtesy of the Parliamentary Estates Directorate.

Portcullis House, Westminster.
To improve summertime performance, water at around 13°C is extracted from a chalk aquifer 150 m under the building and used to cool the fresh air supply.

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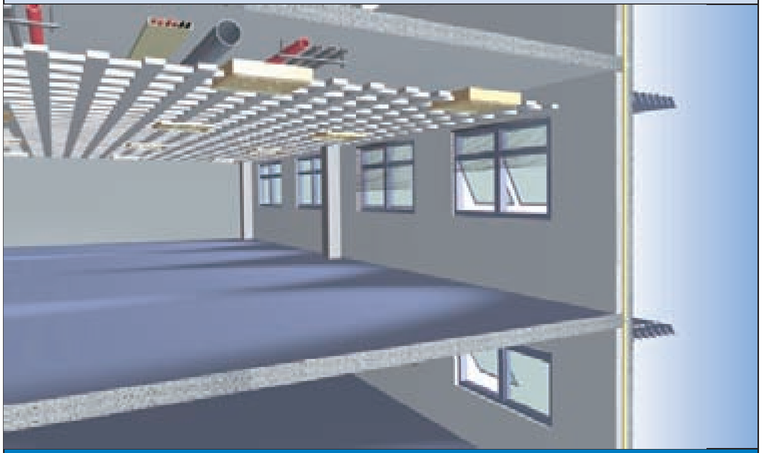
* See page 6
** See page 22

Permeable ceilings allow a compromise to be achieved between exposing the slab and providing a suspended ceiling.

PERMEABLE CEILINGS

DESCRIPTION:
Suspended ceiling with perforated tiles, allowing some thermal linking between the slab and occupied space.



TYPICAL APPLICATIONS:
New build and the retrofit of existing office buildings from the 1960s & 70s
FES COOLING CAPACITY:
Dependent on open area and ceiling type, but should provide approximately 10 W/m^2 in naturally ventilated buildings [32]
KEY BENEFITS:
• A low cost solution that can prevent or reduce the frequency of overheating in new and existing offices, and avoid/reduce the use of mechanical air-conditioning • Allows the use of a suspended ceiling, avoiding the need to route services elsewhere to exploit the thermal mass available in the slab
KEY CONSIDERATIONS:
• Overall effectiveness is a compromise between maximising FES performance and concealing services • May have implications for the acoustic and daylighting performance of the space
CASE STUDIES:
Parkside (British Telecommunications plc), Coventry [12]

Maximising thermal mass in existing office buildings ideally requires the removal of any suspended ceiling system. Unfortunately, this is not possible in many buildings dating from the 1960s and 1970s due to the poor nature of the surface beneath or the impracticality of relocating ceiling located services. However, it is possible to access the thermal mass in the slab by using permeable ceiling tiles, such as the 'egg crate' variety. Other options include the use of horizontal slates which mask the underside of the slab when viewed from an angle, or commercially available perforated ceiling tiles, which provide a more conventional appearance. The use of permeable or partially suspended ceilings is equally applicable to contemporary building design. One technique used on several new-build projects is to leave a gap in the ceiling tiles around the perimeter of the space, which allows fresh air from the windows to enter the void and travel across the slab before dropping down through the tiles [24].

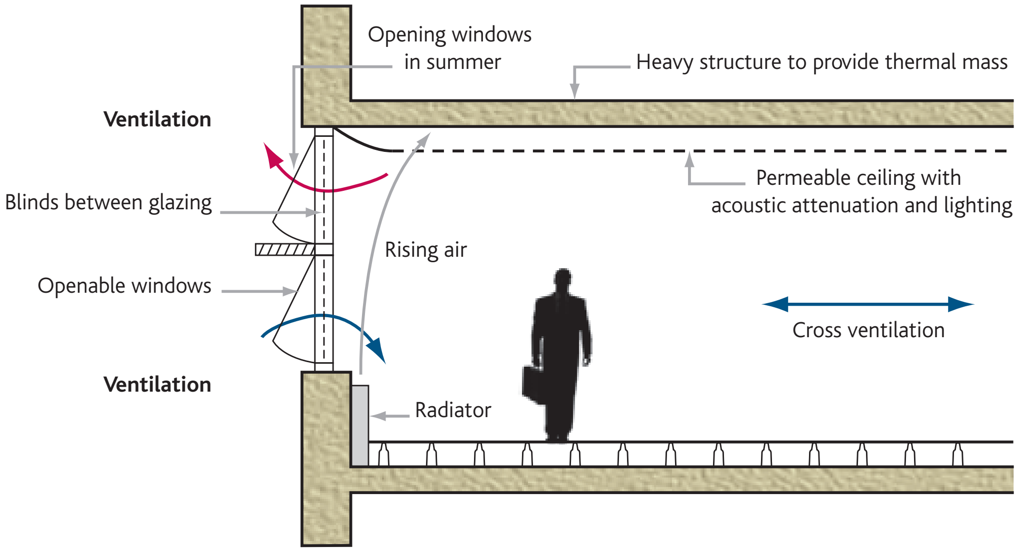
Example of a permeable ceiling, courtesy of Armstrong Building Products.

BSRIA undertook a thermal modelling exercise to gauge the significance of using a conventional suspended ceiling (i.e. non-permeable) on FES performance [14]. The research compared the performance of an exposed soffit to a suspended ceiling, in a room fitted with underfloor ventilation. The results showed that the suspended ceiling increased the temperature in the space by close to 1.5°C compared with the exposed soffit. This figure takes account of the reduction in heat load afforded by air extracted through the type of luminaries typically used in suspended ceilings, which remove much of the heat produced by lamps at source. The research showed that if extract luminaries are not used, the temperature increase will be approximately 2.0°C. These figures provide a good indication of the impact that suspended ceilings have on FES performance.

Whilst permeable ceilings are not as effective as a fully exposed soffit, they do provide a compromise solution by allowing a degree of thermal linking between the room air and slab. Thermal performance varies with the type of slab, ceiling tile and percentage of open area. For perforated ceiling tiles, an open area of 20% is about the maximum that can be used if the slab is to remain hidden. An open area of 20% will allow about 40% of the convective heat transfer that would occur with a fully exposed slab [32].

For offices with mechanical ventilation and a conventional suspended ceiling, a second option exists known as CoolDeck, which improves the convective heat transfer by approximately five times [33]. Whilst this system can be used in conjunction with conventional suspended ceilings, the radiative cooling effect provided by an exposed slab will be absent. To a large extent this is compensated for by the improved convective heat transfer, but this must be balanced with the increased fan power that is necessary to provide the turbulence.

SECTION THROUGH BT PARKSIDE OFFICE SHOWING PERMEABLE CEILING VENTILATION PATH [12].

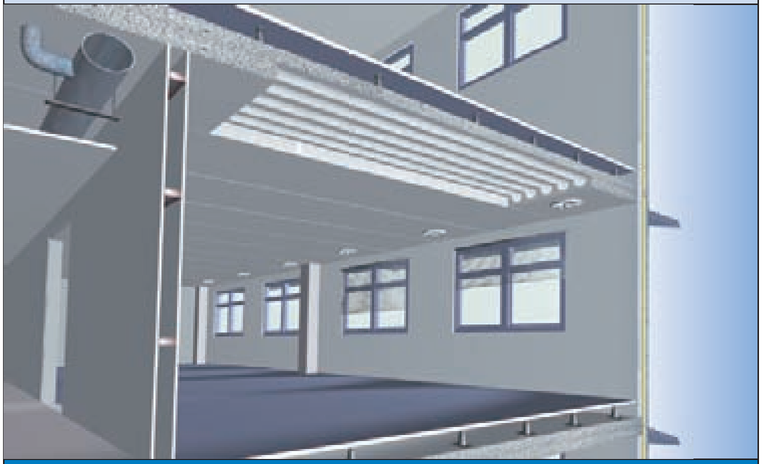


The hollowcore FES system is a well established technology in the UK.

EXPOSED HOLLOWCORE SLABS WITH MECHANICAL VENTILATION

DESCRIPTION:

Precast, hollowcore concrete slabs with mechanical ventilation via the cores, which provides good convective heat transfer between the air and slab. Further heat transfer is provided by the exposed underside of the slab. The system is typically referred to by the trade name 'Termodeck'.



TYPICAL APPLICATIONS:

Universities, schools, theatres, offices (owner occupied)

FES COOLING CAPACITY:

≈ 40 W/m^2 (basic system)
≈ 50 W/m^2 (with cooling)
≈ 60 W/m^2 (with cooling and switch-flow)

KEY BENEFITS:

- Well established technology with good year-round performance
- Clear spans of up to 16 m are possible
- Can be used as a full mechanical or mixed-mode system
- Air can be introduced at high level from diffusers linked to the slab cores, or at low level using an underfloor supply system, with the floor void acting as a plenum

KEY CONSIDERATIONS:

- The slab cores may require periodic cleaning (access points are provided)
- Typical applications in the UK suggest it is a system suited to owner occupied buildings

CASE STUDIES:

- Peel Park, Blackpool [34]
- The Ionica building, Cambridge [35]
- The Elizabeth Fry building, University of East Anglia [36]
- Meteorological Office, Exeter [37]
- Boots Library, Nottingham Trent University

Hollowcore floor slabs are pre-tensioned precast concrete elements with continuous hollowcores to reduce self-weight and achieve structural efficiency. This type of slab can be used very effectively for FES, with mechanical ventilation used to channel air through the cores before entering the occupied space.

Atrium at the Boots Library, Nottingham Trent University, courtesy of Termodeck (Architect: ECD Architects).

The hollowcore system passes supply air through the cores at low velocities, allowing prolonged contact between the air and slabs for good heat transfer. The temperature difference between the slab and the air leaving the cores is not more than 1-2°C. The precast slabs are usually 1200 mm wide, approximately 250-400 mm deep (depending on span), incorporating up to five smooth faced extruded holes along the length. Three of these are used to form a three-pass heat exchanger in each slab, linked to a supply diffuser located on the soffit.

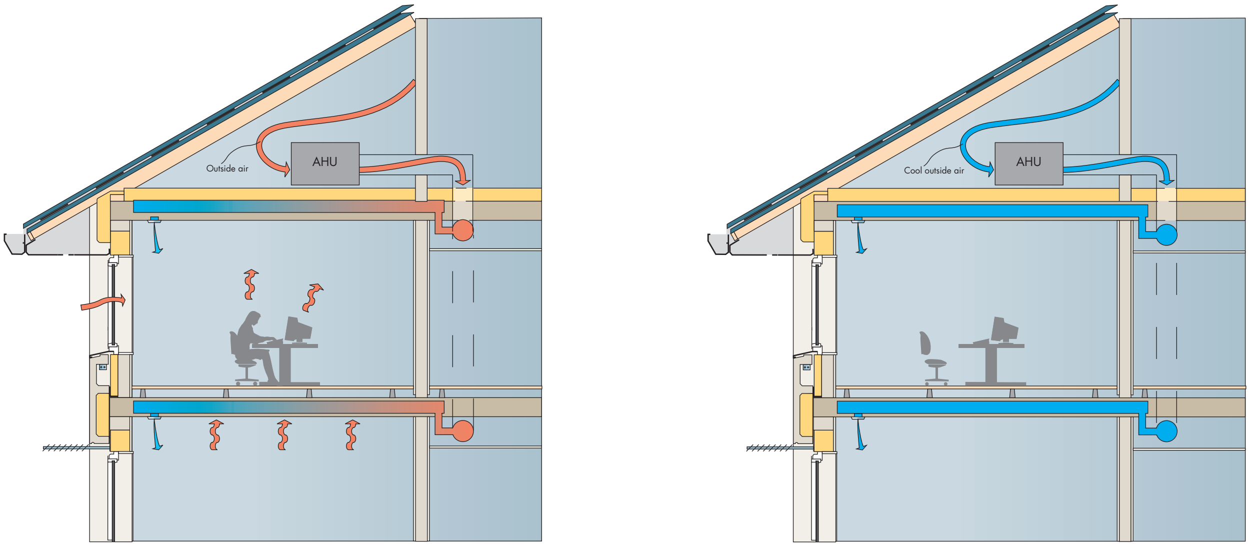
Alternatively, displacement ventilation can be used by ducting the air into an underfloor ventilation system. Air supply to the slabs is via a main supply duct, typically located in an adjacent corridor above a false ceiling. Stale air is generally extracted into a central corridor plenum and then drawn back to the plant room. As with other FES systems, radiant cooling is also provided by exposing the underside of the slab. Supply diffusers should be located about 1-2 m from windows to prevent potential down draughts and/or clashing with partitions. If required, pre-drilled and sealed openings at mid span will make it possible to relocate diffusers in the future. This enables conference rooms or similar spaces to be accommodated in the centre of the building if required.

Typical applications for the hollowcore system include universities and colleges. A much quoted example is the exceptionally low energy Elizabeth Fry building at the University of East Anglia. This four-storey building has a gross floor area of 3250 m^2 and a total energy consumption of approximately 90-100 kWh/m^2/y [36], well below the good practice values for building types 1, 2 and 3 described in ECON 19 [10], all of which share attributes with the Elizabeth Fry building.

The system can be configured to suit a variety of applications and cooling duties. In a basic form it can handle loads of up to 40 W/m^2, although recent experience at the Meteorological Office in Exeter shows that higher loads of around 47 W/m^2 are possible with careful design [37]. The addition of mechanical cooling can increase the cooling capacity of the basic system to 50 W/m^2. Performance can also be increased through indirect evaporative cooling, which cools the supply air without increasing its moisture content. The additional cooling provided by an evaporative system is dependent on ambient conditions, along with the efficiency of the humidifier and heat exchanger, but can lower the air temperature by several degrees under average conditions.

The highest cooling performance is provided by using a switch flow system. This adjusts to individual room temperatures and can be used in conjunction with mechanical and evaporative cooling. The system is regulated by a 'switch unit' that incorporates a changeover damper to reroute the supply air. When a room has to be cooled, the air supply route through the slabs is changed directly to the core that contains the ceiling diffuser, rather than the normal route through all three cores. The shorter distance helps prevent the supply air taking heat from the slab.

HEAT TRANSFER CYCLE OF THE HOLLOWCORE VENTILATION SYSTEM



SUMMER DAYS
During the day, the warm outside air is cooled as it passes through the cores in the slab. The cool concrete structure also absorbs heat generated from lighting, equipment, people and re-radiated solar gains.

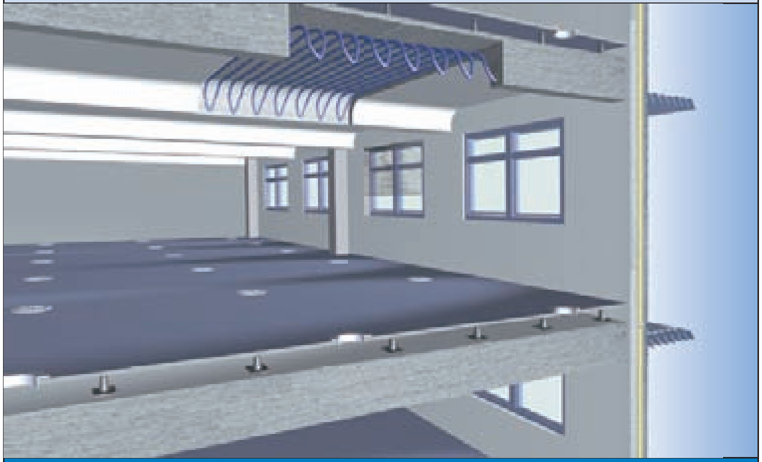
SUMMER NIGHTS
During the night, the air supply fans bring the cool outdoor air into the hollow core slabs and the building fabric is cooled.

Water-cooled slabs can provide up to 80 W/m² of cooling, making them suitable for more demanding applications.

WATER-COOLED SLABS

DESCRIPTION:

Precast or cast in situ slabs with water cooling via embedded polybutylene pipework, which can be used in conjunction with a night time ventilation strategy. The precast option is trade marked 'Thermocast'.



TYPICAL APPLICATIONS:

Offices, museums, hotels, universities, showrooms

FES COOLING CAPACITY:

≈ 64 W/m² (flat slab)
≈ 80 W/m² (profiled slab) [39]

KEY BENEFITS:

- Minimal maintenance
- High cooling capacity
- Provides a combined solution for heating and cooling
- The ability to use high chilled water temperatures may allow the option of free cooling from boreholes, lakes and evaporative coolers
- Precast beams can be designed and manufactured on an individual project basis, with each unit factory tested before dispatch

KEY CONSIDERATIONS:

- The control system must ensure that the slab temperature does not fall below the dewpoint of the internal air, or condensation may form
- For high load applications, water from free cooling sources may need supplementing with mechanical chilling under peak load conditions

CASE STUDIES:

- Barclays Bank/Basilica, Basildon [40,42]
- National Maritime Museum, Greenwich [43]
- British Museum, London

The use of water rather than air to cool floor slabs enables higher cooling capacities to be achieved, making this technique suitable for a broad range of applications. Five layer polybutylene pipe is embedded in the slab about 50 mm below the surface, through which water is circulated at approximately 14-20°C during the summer and 25-40°C during the winter for heating. The technology is applicable to cast in situ and precast slabs. The precast option comprises coffered slabs made in spans up to 16 m in length, providing up to 80 W/m² of cooling [38]. The overall specification, developed on an individual project basis, is factory tested before delivery to site. Manufacturer's details are available from The Concrete Centre.

The British Museum, Great Court features a water-cooled floor system that is used to both cool and heat the space. (Architect: Fosters & Partners)

The good thermal linking between the concrete and the circulating water significantly increases the response time of the slab. This is because resistance to heat flow between the water and slab is about 100 times less than the resistance when using air to cool the slab, after allowing for the difference in heat transfer surface area [44]. The increased response time allows greater flexibility in the night cooling strategy. In naturally ventilated buildings, maximum use can be made of conventional night cooling of the slabs with fresh air, followed by water cooling if required. The relative speed of the water cooling ensures that a combined night cooling control strategy can achieve the required start of day condition in the time available. It takes around 30 minutes for a change in water temperature to have a discernible effect on the surface temperature [42].

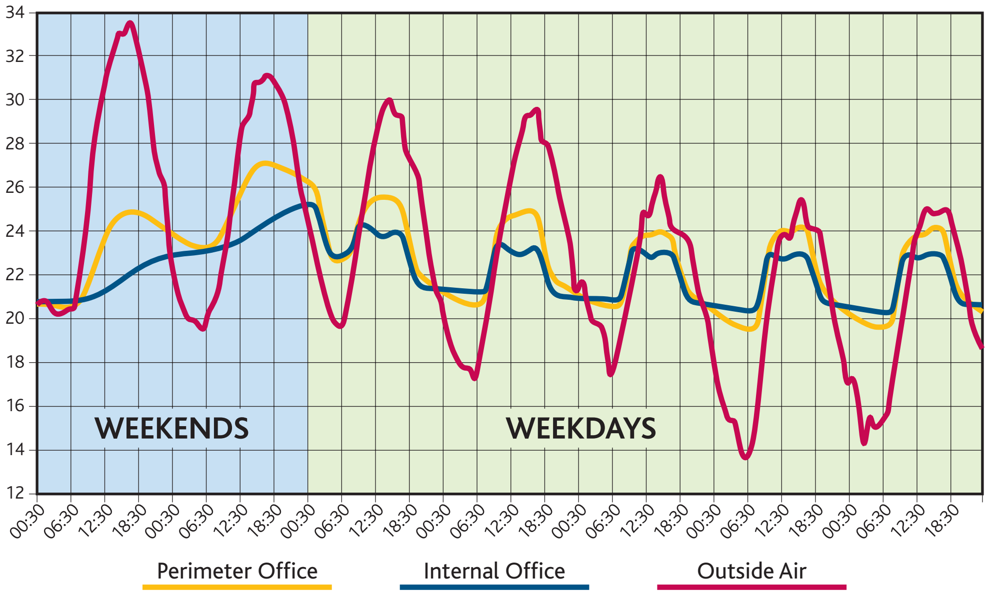
Water cooling is not limited to night operation and can be used as required during the occupied periods to maintain a stable internal temperature. This can prove useful under peak load conditions, when the slab temperature might otherwise increase to a point where overheating is experienced. The relatively short response time of the water cooling makes it possible for the control system to respond to a rise in internal temperature as it occurs.

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 that is necessary to avoid condensation problems allows use of water from sources such as rivers, lakes and boreholes. Depending on the load profile, these sources have the potential to meet the cooling demand on a year-round basis. In recent years, the use of boreholes has grown in popularity. This has been driven by a number of factors including the increasing use of chilled beams/ceilings, the ability to avoid the installation of heat rejection plant and a rising water table that makes obtaining an extraction licence relatively straightforward. The temperature of the extracted water remains steady all year. At Portcullis House, Westminster, water is extracted at around 13.5°C [27]. Lakes and rivers can also be an effective option, but temperatures will be less stable across the year and may be too warm during the summer to meet the full cooling load [41]. When using natural water sources, a plate heat exchanger (PHE) separates the chilled water circuit, preventing the occurrence of fouling in the pipework. This will incur an approach temperature of approximately 1.25-2°C, which must be accounted for when considering the ability of a natural water source to meet the required chilled water temperature, especially under peak loads.

Full time mechanical chilling can be used where natural sources are not an option. However, opportunities still exist to save energy by applying a free cooling technique appropriate to the plant used [38]. The elevated chilled water temperature can make this cost effective, especially where high cooling loads occur for relatively long periods.

The ability to run the chiller(s) at night to cool the slab enables cheap rate electricity to be used, providing further financial savings over conventional air-conditioning systems. Capital savings are possible with the chiller plant, which, as it does not have to meet peak cooling loads due to the stabilising effect of the slabs, can be comparatively small for the size of building.

Internal temperature of an office with the Thermocast system during a hot July week. The temperature remains at a comfortable level during the occupied period, and only exceeds 26°C during the weekend when the cooling system is not operational. The graph was produced by Buro Happold, as part of a thermal modelling analysis of the Thermocast system [39].



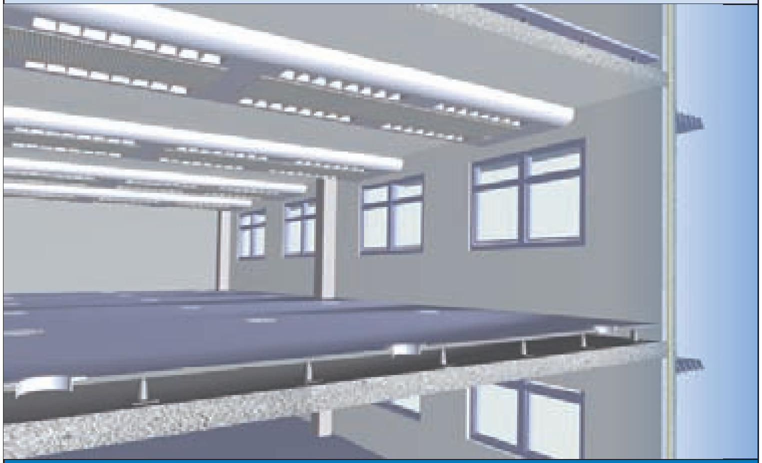
In recent years the combination of chilled beams and exposed concrete soffits has become an increasingly popular solution.

An example of a chilled beam system. Homer Road office project, Solihull, courtesy of Foggo Associates (Architect: Foggo Associates).

CHILLED BEAMS, WITH EXPOSED OR PARTIALLY EXPOSED SOFFITS

DESCRIPTION:

Concrete soffits (flat or coffered) with chilled beams suspended directly below. A permeable ceiling may be used, or the soffit left exposed. FES is provided in the usual way, using natural and/or mechanical ventilation.



TYPICAL APPLICATIONS:

Offices, universities, refurbished 1960s/70s office buildings

FES COOLING CAPACITY:

≈ 15-30 W/m^2 (FES only). Cooling capacity is dependent on the type of ventilation and surface area of the soffit, etc. Chilled beams can provide additional cooling as required, up to a maximum of 100-160 W/m^2

KEY BENEFITS:

- Low maintenance (compared with other ceiling based air-conditioning systems)
- Quiet, draft free operation
- Relatively shallow unit depth makes chilled beams ideal for refurbishment projects with a low slab to slab height, especially where a raised floor is required
- Provides a high cooling capacity while still making effective use of FES
- The use of high chilled water temperatures may allow free cooling from boreholes, lakes and evaporative coolers, etc.

KEY CONSIDERATIONS:

- Water flow temperatures must be carefully controlled to avoid condensation problems
- Where possible, beam positions should not restrict air flow across the soffit
- If used in conjunction with a permeable ceiling, the open area must be maximised to promote air flow in the void

CASE STUDIES:

- Barclaycard Headquarters, Northampton [41]
- Homer Road, Solihull [45]
- City Campus Learning Centre, Leeds Metropolitan University [38]

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 (MSCB) 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 a building by supplementing the passive cooling provided by thermal mass.

A chilled beam is a simple long rectangular unit enclosing a finned tube through which chilled water is pumped. The beams are mounted at a high level where surrounding air is cooled, causing it to lose buoyancy and travel downwards into the occupied space below. Cooling is largely convective, so good air flow around the beams is essential. Air flow can be maximised by suspending beams directly from exposed soffits.

Suspended ceilings must have a large open area, typically greater than 50% [17]. The maximum cooling output from chilled beams is in the order of 100-160 W/m^2 [46]. Further cooling capacity is provided by FES, and potentially from the ventilation system as well if the fresh air is conditioned. Ventilation is essentially a separate provision, generally via either natural ventilation or a mixed-mode underfloor system. Fresh air can also be ducted directly to the beam, but this approach will limit FES performance.

Chilled 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. Alternatively, it is possible to use water pumped directly from evaporative coolers, which can satisfy the load for much of the year. This technique has been used to good effect at Leeds Metropolitan University [38].

FES can be employed using techniques described in this publication, with the chilled beams operating during the daytime to boost the overall cooling capacity. In some installations, especially those using natural water sources or other forms of free cooling, it may be advantageous to also operate the beams at night during hot weather. This can supplement the night cooling by ventilation, helping to remove heat from the slab.

The thermal interaction between the occupied space, chilled beams and slab is highly dynamic, and dependent on variables such as air velocity, air temperature and control strategy. CFD modelling is necessary when an accurate assessment is required.*

MSCBs offer a particularly attractive option since they combine a range of services in addition to cooling, which can include any or all of the following:

- Lighting systems
- Sprinkler systems
- Smoke detectors
- Public address systems
- Voice, data and BMS cabling
- Passive Infra-Red (PIR) sensors
- CCTV
- Acoustic control panels

In existing buildings where the slab to slab height is limited, chilled beams are a convenient way of incorporating cooling and other services in a minimal ceiling depth. Typically, a minimum required depth is around 300 mm, however shallower depths are possible. This is useful when refurbishing typical 1960s office buildings which often present a low floor to ceiling height. Incorporating a raised floor into these buildings can be difficult, but can often be achieved if a chilled beam system is used. A good example of a refurbished 1960s property is the Empress State Building, London which is an ex-Ministry of Defence office block [47]. Chilled beams were used as part of the conversion of the floors into modern office space. The beams incorporate cooling, lighting, PIR sensors, primary fresh air and speakers, all in a depth of around 280 mm. They were suspended directly from the slab which was left exposed.

Basic chilled beams can also be used as part of a permeable ceiling system,** useful in existing buildings where the surface finish of the slab is poor. In this type of application the cooling coil can be left largely exposed, saving the cost of any casing. The open area in the ceiling should be as large as possible to maximise the air flow over the beam and across the slab.

Chilled beams can be custom made to specific requirements, allowing them to be sympathetic to the overall aesthetics of the interior. Lighting can also be configured to provide a particular effect; for example uplighters can be incorporated to avoid dark soffits. Acoustic panels can be included to minimise reflected sound from the soffits.

Chilled beam system showing the use of uplighting to illuminate the soffit, courtesy of Frenger Systems Limited.

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* See page 7
** See page 16

High thermal mass buildings can make a significant contribution to whole life performance, by avoiding or reducing the need for air-conditioning.

SUMMARY

Exploiting concrete's thermal mass provides an effective means of maintaining a comfortable environment in many building types, while producing low or zero carbon dioxide emissions. It is an increasingly important technology that can lessen the extent to which the operation of buildings contributes towards climate change.

At the same time, the rising temperatures linked to climate change make it increasingly important that buildings are designed to limit overheating both now and in the years to come, when the problem is predicted to become more acute [48]. This is a requirement in the 2004 revision to Part L of the Building Regulations, which encourages passive measures to minimise overheating.

High thermal mass buildings therefore contribute positively towards a good whole life performance, and offer an attractive design solution given the background of rising energy prices, and changes to the Building Regulations. There is also a growing realisation that a lack of sustainable design can have a direct impact on the long-term desirability and value of commercial developments. These factors present a strong case for the use of precast or cast in situ concrete floor slabs to achieve comfortable, cost effective and more sustainable buildings.

BENEFITS OF USING CONCRETE FOR LOW ENERGY COOLING

- High thermal mass and exposed soffits make cast in situ and precast concrete slabs ideally suited to FES.
- The combination of underfloor ventilation and exposed soffits can unlock the thermal mass in slabs of 250 mm and more.
- Avoiding suspended ceilings can reduce building height and reduce construction costs.
- The finish of exposed concrete soffits can be used to assist daylight penetration.
- The density of cast in situ and precast floor slabs helps minimise transmission of structure-borne sound.
- Experience shows that exposed concrete systems provide a comfortable and productive environment.
- As climate change continues to drive up temperatures, the potential exists for serious growth in the use of energy intensive air-conditioning. The high thermal mass provided by concrete building solutions provides a more sustainable alternative, which can significantly reduce CO_2 emissions over the life of a building.

RSPCA Headquarters, West Sussex, courtesy of whitbybird.
Photography: Jaap Oepkes.

REFERENCES

1 Climate Change and the Indoor Environment: Impacts and Adaptation, TM36, Chartered Institute of Building Services Engineers (CIBSE), 2005.
2 Guide A – Environmental Design, CIBSE, 1999.
3 Glass J, Ecoconcrete, British Cement Association, 2001.
4 BRECSU, Avoiding or Minimising the Use of Air-Conditioning, Report 31, HMSO, 1995.
5 The Impact of Thermal Mass on Building Performance, Arup Research & Development, CCANZ, 2004.
6 Natural Ventilation in Non-Domestic Buildings, BRE Digest 399, 1994.
7 Martin A, Fletcher J, Night Cooling Control Strategies, Technical Appraisal TA14/96, BSRIA, 1996.
8 Maria K, Night Ventilation for Cooling Office Buildings, Information Paper IP4/98, BRE, 1998.
9 Barnard N, Concannon P, Jaunzens D, Modelling the Performance of Thermal Mass, Information Paper IP6/01, BRE, 2001.
10 Energy Consumption Guide 19, Energy Use in Offices, Energy Efficiency Best Practice Programme, 2003.
11 ODPM, Current Thinking on Possible Future Amendments of Energy Efficiency Provisions, Part 5, 1999.
12 Ward IC, Energy and the Environmental Issues for the Practising Architect, Thomas Telford Publishing, 2004.
13 For further information visit the Cement and Concrete Association of New Zealand website (www.cca.org.nz).
14 Barnard N, Dynamic Energy Storage in the Building Fabric, Technical Report TR9/94, BSRIA, 1995.
15 Building Energy and Environmental Modelling, Application Manual AM11, CIBSE, 1998.
16 Oseland N, A Review of Thermal Comfort and Its Relevance to Future Design Models and Guidance. Proceedings from BEPAC Conference (pp 205 -216), York, 1994.
17 Gold CA, Martin AJ, Refurbishment of Concrete Buildings: Structural and Services Options, Guidance Note GN 8/99, BSRIA, 1999.
18 Control of Natural Ventilation, Technical Report TN11/95, BSRIA, 1995.
19 Martin A, Fitzsimmons J, Making Natural Ventilation Work, BSRIA Guidance Note GN 7/2000, BSRIA, 2000.
20 Sustainable Buildings Are Better Business – Can We Deliver Them Together?, Arup Associates, British Council for Offices, 2002.
21 Mixed-Mode Ventilation, Application Manual AM13, CIBSE.
22 The Cost of Going Green, Reinforcing Links, Reinforced Concrete Council, September 1996.
23 Case Studies of Low Energy Cooling Technologies (International Energy Agency, Annex 28), Faber Maunsell, 1998.
24 Martin A, Kendrick C, Booth W, Refurbishment of Air-Conditioned Buildings for Natural Ventilation, Technical Note TN8/98, BSRIA, 1998.
25 New World Headquarters for Vodafone, Concrete Quarterly, Issue 197, 2000.
26 O'Neill BT, Shaw G, Flynn M, PowerGen Headquarters (Project Profile), British Cement Association, 1996.
27 Bunn R, Lord of The Files, Building Services Journal, September 2000.
28 Thornton JA, Deavy CP, Mitchell DM, The New Parliamentary Building – Portcullis House, A paper presented at the Institution of Structural Engineers 2000.
29 Braham D, Barnard N, Jaunzens D, Thermal Mass in Office Buildings – Design Criteria, BRE Digest 454 part 2, BRE, 2001.
30 Gody R, Willis S, Bordass B, Cutting out the Cooling, Building Services Journal, April 1994.
31 Best Practice in the Specification of Offices, British Council for Offices (BCO) Guide 2000, BCO, 2000.
32 Kendrick C, Permeable Ceilings for Energy Storage, Building Services Journal, August 1999.
33 Barnard N, Thermal Mass and Night Ventilation – Utilising "Hidden" Mass, 2003 CIBSE/ASHRAE conference.
34 Bunn R, Mass Control (Building Analysis: Peel Park), Building Services Journal, November 1997.
35 Case Studies of Low Energy Cooling Technologies, the Ionica Office Building, Cambridge (International Energy Agency, Annex 28), Faber Maunsell, 1998.
36 Probe 14 - Elizabeth Fry Building, Building Services Journal, April 1998.
37 Kennett S, Location Location Location?, Building Services Journal, June 2004.
38 De Saulles T, Free Cooling Systems, Guide BG 8/2004, BSRIA, 2004.
39 Buro Happold, Thermal Performance of the Thermocast System, Research Report 008939 for Tarmac plc, 2004.
40 Bunn R, Cold Silence, Building Services Journal, March 1999.
41 Probe 20 - Barclaycard Headquarters, Building Services Journal, March 2000.
42 Arnold D, Othen P, What a Mass, HAC, 2002.
43 Under Floor Heating and Cooling, ENERGIE Technical Note, BSRIA, 2001.
44 Arnold D, Building Mass Cooling – Case Study of Alternative Cooling Strategies, CIBSE National Conference 1999.
45 Dawson S, Solihull Hybrid Sheds Light on Office Design, Concrete Quarterly, Issue 209, 2004.
46 De Saulles T, The Illustrated Guide to Mechanical Building Services, Guide AG/15, BSRIA, 2002.
47 Trox Technik, Multi-Service Chilled Beams, September 2002.
48 Too Hot to Handle, Building, 6 August 2004.

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Atrium at Portcullis House, Westminster (Architect: Michael Hopkins & Partners).

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