THE INSTITUTE OF CONCRETE TECHNOLOGY
ANNUAL TECHNICAL SYMPOSIUM
28 March 2006

CONCRETE FOR A SUSTAINABLE FUTURE

Thermal Mass in Commercial Office Design

Tom De Saulles
BEng CEng MCIBSE MIMechE

British Cement Association
The Concrete Centre

Have been unable to alter the references from Roman to Arabic numbers.

Edited PCO/GT 25/05/06

ABSTRACT: This paper discusses the various issues and techniques that relate to the application of high thermal mass exposed concrete floor slabs in commercial office design. It also considers the relative difference between the embodied CO_2 of concrete and the in-use savings in CO_2 which it can provide through operational energy savings.

Keywords: Thermal mass, Mixed-mode, Thermal linking, Coffered slab, Embodied CO_2, Overheating, Night cooling, Diurnal temperature, Floor plenum, Free cooling, Ground water.

Tom De Saulles: Tom De Saulles is the Building Sustainability Manager at the British Cement Association, specialising in energy use in buildings, particularly the application of passive heating and cooling techniques. Tom previously spent ten years working for the Building Services Research and Information Association (BSRIA), where he researched and compiled a number of publications for the construction industry including illustrated guides on building services systems and design guidance on free cooling. He is a chartered building services and mechanical engineer, and is currently compiling a thermal mass design guide.

INTRODUCTION

The case for using thermal mass in office design is now stronger than ever, and is supported by a wide range of techniques that exploit the excellent thermal properties of concrete floor slabs. These range from the simple combination of an exposed slab and night ventilation, to the relatively new approach of using water to regulate slab temperature. The increasing use of thermal mass for passive cooling is largely being driven by a combination of rising energy prices and the need to build more sustainability to help mitigate the rapid onset of climate change, whilst also adapting to the impact of rising temperatures. Despite the benefits that concrete has to offer in terms of thermal mass, there is often a reluctance to specify concrete due to a perception that its embodied impacts are more significant than its energy saving potential. However, new research commissioned by The Concrete Centre/BCA and undertaken by Arup has shown that the opposite can be true providing the thermal mass is effectively utilised.

THE ARCHETYPAL OWNER-OCCUPIED HIGH THERMAL MASS OFFICE

Over the last two decades the UK has experienced significant growth in the demand for air-conditioned offices, typified by the ubiquitous speculative development, incorporating variable air volume (VAV) or fan coil systems. However, the 1990s also saw some of the larger owner/occupier construction clients opting for a night-cooled, high-mass solution when procuring a new headquarters or other high profile building. These low energy concrete frame buildings share many similar features, suggesting that they have, to a large extent, achieved an optimal design solution. This type of development has proved to be very successful and continues to be built today; however, the design techniques they employ have largely failed to transfer into the more mainstream speculative office market. To some extent, this is starting to change as tenants consider more carefully the running costs of highly serviced buildings and their desirability if it becomes necessary to sublet the property. The challenge for developers and designers is to apply the lessons learned from existing prestigious owner-occupied high thermal mass buildings into the commercial market, whilst maintaining the essential building requirements that tenants expect.

The owner- occupied offices mentioned above use a combination of thermal mass and night cooling as an alternative to mechanical air-conditioning. In addition to providing reduced operating costs and a good working environment, the typical client brief also required demonstrable evidence of their organisation's 'green' credentials. In meeting these needs, a popular solution was, and continues to be, a concrete-frame building with exposed soffits capable of providing a high level of thermal mass. Night cooling is used to purge heat built up in the slab during the day, ensuring a relatively stable internal temperature during hot weather; a technique that is well suited to the relatively high diurnal temperature swing experienced in the UK.

Typically, the form of these buildings is characterised by long narrow floor plates, usually with a central atrium to allow a high rate of natural ventilation and good daylight penetration. This configuration has proved very successful and has become a standard approach for this type of building. The floor slabs, which may be either cast in situ or precast are typically coffered, and are a key component in the design, since they help fulfil the functional, structural, aesthetic and acoustic requirements of the brief in a single element. In comparison to a flat slab, the formation of coffers or other profiled finish can approximately double the surface area[i] and enhance overall heat transfer by up to 25%. The shape of the coffer is also designed to improve the acoustic performance of the office by focussing noise onto acoustically absorbent wings that form part of the suspended light fittings located below each coffer. Typical, a peak temperature reduction of around 3ºC can be achieved over a 24-hour cycle[i]. Slab thickness is usually between 200 and 300 mm, which provides sufficient heat capacity to help prevent overheating during extended periods of hot weather. The combination of exposed concrete soffits with a natural ventilation night cooling strategy can offset heat gains of approximately 20 W/m^2 providing the diurnal temperature swing is at least 5ºC [ii]. The increased surface area provided by forming coffers or troughs can increase this to 25 W/m^2.

To date, these high thermal mass offices have largely been the preserve of the owner/occupier construction client, whose design brief reflects their intention to operate the building over a relatively long period, thus making steps to reduce operating and business costs a worthwhile investment. At the other end of the market, property developers and investors such as the large insurance providers, generally opt for safe, low risk designs which can be easily let and provide a short payback. A belief that sustainable construction is prohibitively expensive has generally acted as a barrier to its uptake. However there is evidence of a change in this sector which includes projects such as the National Trust HQ in Swindon, Plantation Place in London and Belvedere Court in London[iii]. Other examples of concrete frame, high-mass speculative office developments include Number One, Leeds City Office Park and the Addison Wesley Longoman office in Harlow[iv].

BRINGING THERMAL MASS INTO MAINSTREAM OFFICE DESIGN

Monitored data and occupant feedback from several owner/occupier high mass offices provides good evidence of their relatively low energy consumption and comfortable internal environment[v,vi,vii,viii]. The general success of these buildings in meeting their brief is not in question and they will no doubt continue to be built throughout the UK. However, the challenge remains one of transferring and adapting the technology into a speculative office context, and finding practical design solutions that meet the operational and financial demands of this market. In addition to the technical challenges, there is also the issue of occupant control, which is a major factor in the success of high thermal mass buildings, especially those that use natural ventilation. For individuals used to playing no part in the control of their environment, it is vital that they understand the design intent of their office and the impact that their actions can have on comfort and energy use. This requires more than a 10-minute briefing, and is an important part of the handover process. In many ways this is harder for the tenant of a speculative office who, unlike owner/occupier organisations, is unlikely to have had any involvement in the design process and may have a lower threshold of commitment in helping ensure the building functions as intended. For this and other practical reasons, it may well be that the design is less reliant on natural ventilation which typically requires a high degree of occupant control, and favours instead mechanical ventilation or water cooling of the floor slabs. This and other technical design issues are examined in the remainder of this paper.

Ceiling voids

A major barrier to the uptake of thermal mass is the use of suspended ceilings to conceal services and located luminaries, etc. Whilst this is a convenient solution for the speculative office market, which requires flexibility and convenience, it is largely incompatible with passive design. Permeable ceilings provide a compromise solution by allowing a degree of thermal linking between the room air and slab. An open area of 20% is about the maximum that can be used if the slab is to remain hidden[ix]. Thermal performance of permeable ceilings varies with the type of slab, ceiling tile and percentage of open area. Research undertaken by Oxford Brooks University suggests that an open area of 20% will allow about 40% of the convective heat transfer that would occur with a fully exposed slab[ix]. However, the use of perforated metal tiles with the acoustic backing removed, does allow some heat to be absorbed and re-radiated, thus increasing the radiative heat transfer. Permeable ceilings therefore offer a compromise where the services cannot be moved and/or profiled metal decking needs to remain hidden from view.

Multi-service chilled beams offer another means of exposing the slab, by offering a convenient and neat solution for locating ceiling services and providing the additional cooling capacity sometimes required in more challenging environments. The beams are directly suspended from the underside of the slab, and can also be designed to incorporate sound-absorbing panels to deal with sound transmission problems that can occur.

Mixed-mode ventilation and air conditioning

The use of a mixed-mode (natural and mechanical) ventilation solution has proved to be a popular option in the owner/occupier high thermal mass office, as it provides greater overall control of ventilation and internal temperature. The need for a mixed-mode solution is likely to be even stronger for the speculative office market, which does not generally have the benefit of green field sites and atrium-enhanced natural ventilation. Additionally, the noise and security issues that can result from openable windows may preclude the use of natural ventilation alone, especially in urban environments. It is also likely that any passive cooling strategy used in a commercial office will be supplemented by mechanical air conditioning to ensure overheating is avoided during very hot weather. This approach has been used at a number of owner occupied buildings including the RSPCA headquarters in West Sussex.

Floor voids

Whilst ceiling voids present a challenge in high thermal mass office design, floor voids are generally beneficial, which is fortunate since exposing the slab will require an alternative location for routing the displaced services. For buildings with mechanical ventilation, the floor void also provides a convenient means of introducing air into the office space via floor-mounted outlets. The void acts as a plenum to distribute the air, allowing some heat transfer between the air and the top of the slab, with the added benefit that less ductwork is required. Where heat transfer is optimised by creating turbulence in the void, it is possible to increase the convective heat transfer, to around 10-20 $W/m^2/K$[x]. The actual rate of heat transfer depends upon achieving a balance between the mean speed of 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 of achieving this is to divide the floor void into approximately square compartments, each containing several diffusers, and supplying each compartment via a damper linked to a central plenum duct running across the floor[xi].

The use of floor voids for fresh air distribution and supply is an established technique and is not a barrier for the use of thermal mass in commercial office design. It does, in fact, offer a number of advantages over ceiling based systems including[iii]:

- A reduction in the resources required to construct the building
- The ability to provide a high proportion of fresh air to the occupants
- Lower maintenance and churn costs
- Lower energy consumption.

Cooling loads

A naturally ventilated high thermal mass office will provide comfortable conditions for environments with a modest cooling load and good solar control. More demanding applications may require the increased performance provided by mechanical ventilation. This can increase the cooling capacity from 25 to 35 W/m^2 [xii], due to the improved convective heat transfer, typically achieved by the use of the floor void as an air supply plenum. A higher performance of 40 W/m^2 is possible using hollow core slabs with forced ventilation, otherwise referred to under its trade name of 'Termodeck'. This has proved to be a popular system in the UK, with around 50 installations to date. Typical applications include university and school buildings, to which it is ideally suited, and has resulted in the exceptionally low energy Elizabeth Fry Building at the University of East Anglia. This 4-storey building has a gross floor area of 3250 m^2, and a total energy consumption of approximately 60 $kWh/m^2/y$ [xiii]. So far, Termodeck has not proved popular for commercial offices, which is largely due to perceived flexibility issues.

Using water to cool the slab provides the highest cooling capacity. This technique uses polybutylene pipes embedded in the slab, through which water is circulated at 14ºC - 20ºC during the summer, providing a maximum cooling capacity of approximately 65 W/m^2. During the winter, a flow temperature of 25ºC - 40ºC can be used to provide heating. In bespoke systems the pipe work is positioned as required and attached to the reinforcing, which keeps it in place when the concrete is poured. Alternatively, water-cooled slabs can be supplied as precast units known in the UK under the trade name of 'Thermocast'. This option has the advantage of enabling pipe work to be tested under factory conditions before dispatch. The coffered slabs can be made in spans up to 13m in length, and can be used in steel frame or in situ structures. A conventional chiller can be used to supply water during the summer which, due to the high flow temperature, can be configured to make good use of free cooling[xiv]. Alternatively ground or lake water can be used, although care needs to be taken with the latter option, which can prove to be too warm during the summer for effective cooling[xv]. The use of ground water is an increasingly popular option in London for all types of office, including a recent speculative development[iii]. The reasons for this include the space saved by avoiding the need for heat rejection plant, and the relative ease in obtaining an extraction licence, helped by a rising water table.

Operational and embodied CO_2 in high thermal mass concrete buildings

Despite the benefits that concrete has to offer in terms of thermal mass, there is often a reluctance to specify it due to a perception that its embodied impacts are more significant than its energy saving potential. Whilst the embodied CO_2 of concrete can be higher than that associated with alternative materials, in many cases the difference is relatively small, and becomes largely insignificant when compared to the savings in operational CO_2 emissions that thermal mass can provide during the life of a building. Designers often fail to recognise this point, tending instead to focus purely on the embodied impacts of construction materials.

In reality, the slightly higher embodied impacts of concrete and masonry products can be offset in relatively few years of operation providing effective use is made of the thermal mass to minimise the energy used for cooling (and in some cases heating as well).

To fully validate this argument the concrete sector commissioned Arup to compare the embodied and operational CO_2 emissions of a simple semi-detached house built using a lightweight frame and also in a traditional masonry format with concrete walls and floors, providing varying levels of thermal mass. The result showed that there is a slightly higher embodied impact in the masonry construction, but that this can be offset in approximately 11 to 25 years (depending on the level of thermal mass) if the thermal mass is used to optimise energy use in summer and winter[xvi]. The thermal modelling undertaken used real weather data, modified to take account of the UKCIP02 climate change scenario, which reflects the most likely changes to UK weather over the 21st century.

Beyond the point at which the additional CO_2 burden in masonry construction is offset, the total CO_2 emission (embodied and operational) becomes less than that of the equivalent low thermal mass version of the dwelling. In other words the whole life CO_2 impact of a masonry house can be lower than an equivalent low thermal mass house if the benefits of thermal mass are exploited.

Whilst the research focused on dwellings, it seems likely that a favourable result may also be achieved with other types of building especially offices, which are likely to experience greater benefits in the summer, and less benefit in the winter since passive solar design is not as relevant.

CONCLUSIONS

The combination of high thermal mass and night cooling is a key technique in the field of sustainable building design, and is set to play an important part in helping commercial office design adapt to the effects of climate change, rising energy prices and more demanding building regulations. It can also contribute to the long-term value and usability of these buildings, ensuring a good return on investment in a commercially driven market.

For many office developments, it looks likely that thermal mass will be combined with mixed mode ventilation, and may possibly be supplemented by air conditioning. There are a number of reasons for this including the need for enhanced cooling performance in more demanding office environments, and the need to overcome issues relating to security, noise and the general letability of buildings. The trend towards the use of urban and brownfield sites may also exacerbate noise and security issues.

Whilst the current focus in sustainable construction is largely centred on the embodied impacts of construction materials, it can be shown that the in-use benefits of thermal mass can offset the higher embodied CO_2 associated with concrete in a relatively few years. This highlights the need to take a more holistic approach to building design, which considers both embodied and in-use impacts during the life of a building.

REFERENCES

[i] Barnard N, Concannon P, Jaunzens D: Modelling the Performance of Thermal Mass, BRE Information Paper IP6/01, Gartson, Watford, Construction Research Communication Ltd, 2001.

[ii] Martin A, Fletcher J: Night Cooling Control Strategies, BSRIA Technical Appraisal TA14/96, Building Services Research and Information Association, Bracknell, Berkshire, 1996.

[iii] Sustainable buildings are better business – can we deliver them together?: Arup Associates, British Council for Offices, 2002.

[iv] Speculative build warms to passive design: Reinforcing Links, Reinforced Concrete Council, Issue 10, 1996.

[v]Annex 28, Low Energy Cooling – Case Study Buildings, International Energy Agency. 1998

[vi] PowerGen Headquarters – Project Profile, Reinforced Concrete Council, 1996.

[vii] Avoiding or minimising the use of air-conditioning. Report 31, Best Practice Programme, BRECSU, Building Research Establishment, Garston, Watford, 1995.

[viii] Martin A, Fletcher J: Night cooling control strategies - BSRIA Final report RR 5/96, 11621/4, Building Services Research and Information Association, Bracknell, Berkshire, 1996.

[ix]Kendrick C: Permeable ceilings for energy storage, Building Services Journal, August 1999.

[x] Barham D, Barnard N, Jaunzens D: Thermal Mass in Office Buildings – Design Criteria, BRE Digest 454 Part 2, Building Research Establishment, Garston, Watford, 2001.

[xi] Bordass B, Gody R, Wills S: Cutting out the Cooling, Building Services Journal April 1994.

[xii] Fabric Energy Storage in Concrete: Reinforcing Links, Reinforced Concrete Council, Issue 9, 1995

[xiii] Probe 14 - Elizabeth Fry Building, Building Services Journal, April 1998

[xiv] De Saulles T: Free Cooling Systems - Design and Application Guidance, BSRIA, Building Services Research and Information Association, Bracknell, Berkshire, 1996.

[xv] Probe 20 - Barclaycard headquarters, Building Services Journal, March 2000

[xvi] Arup Research + Development, A Lifecycle Analysis of Carbon Dioxide Emissions from Housing Under Climate Change – Examining the Role of Thermal Mass, (research sponsored by the TCC / BCA), 2006.