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Case Study of Mixed Mode Building with Chilled Slabs and a Cooling Pond

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Summary

A client was pleased with the performance of a recent building designed and built with low energy objectives on the “mixed mode” principle. When the time came to build another building he appointed the same design and construction team and challenged them to suggest cost effective improvements to the environmental features of the original building. The team developed a "shopping list" of potential energy use reducing features that included chilled slabs, which could be cooled by both a cooling pond and mechanical refrigeration. Fortuitously the site had sufficient space for a cooling pond. This paper is a case study of the design and installation and, commissioning of the building cooled by chilled slabs operating alternately on passive (natural ventilation/cooling pond) and mechanical (refrigeration) cooling.

Background

A client was pleased with the performance of a recent building that had been designed and built with low energy objectives on the “mixed mode” principle (1). The previous building, the Barclaycard HQ is described elsewhere (2,3). It uses overnight ventilation in conjunction with chilled beams to cool the space. The chilled beams are water cooled either passively by a cooling pond or mechanically by a water-chiller using the same cooling pond to reject condenser heat. When the time came to build another building for another company in the group the client appointed the same design and construction team and challenged them to suggest cost effective improvements to the environmental features of the original building.

The design team developed a "shopping list" of potential energy use reducing features that included chilled slabs. Chilled slabs are simply conventional reinforced concrete slabs with continuous serpentine coils of pipe work attached to the reinforcing mesh and buried in the concrete (see figure 1.). The pipe coils are coupled to recirculating cooling water systems. They provide cooling in the same way as a radiant chilled ceiling but can utilise the thermal energy storage capacity (thermal mass) of the structure. Therefore the rate of cooling available is greater than the instantaneous heat removed when the slab is being warmed. And, consequently, can use lower grade chilled or passively cooled water. Fortuitously the site had sufficient space for a cooling pond.

The client was attracted to the use of these slabs to enhance the performance and appearance of the new building but his concerns were, a) the technique was new and untried, b) there was no cost information, c) the performance was unknown and, d) they did not comply with the "Institutional" view of office air conditioning. These concerns were resolved by visiting existing projects in Switzerland and development of the design as described elsewhere (4).

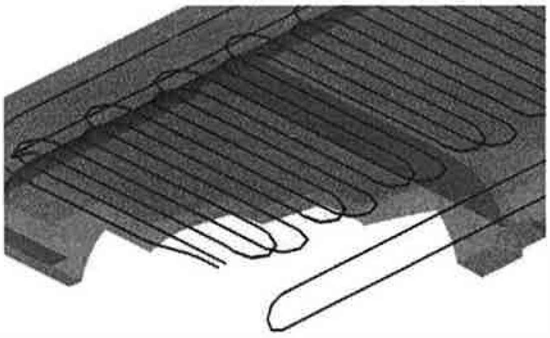

Figure 1. "See through" view from underside of a Chilled Slab

However the slabs in the projects in Switzerland were designed and built to a different performance specification than those planned for this project. Firstly, they were built on site and the concrete poured in-situ whereas the construction programme for this building required pre-cast units. And, secondly the cooling demand in the buildings was much less.

The Client' s Brief

As the new building was to be constructed for a different company in the group this effectively meant a new client with a change of requirements. The "new" client had a more stringent performance criteria for this building and it had to comply or be easily adapted to "Institutional" standards. There was also concern at the consequences of climate change and performance of mixed mode building during extremes of temperature such as several days with peak daily temperatures around 32/33°C.

The additional requirements of the new client made it more difficult to design a low energy building. For example:

a) Higher loads. The heat gains from office equipment were 10 to 15 W/m2 higher than the allowance for the previous building.

b) Lower peak temperatures. The new client was of the opinion that a maximum internal temperature of 25°C was too high. He wanted a maximum of 24°C but was accepted the air temperature could rise to 25°C providing the dry resultant temperature did not exceed 24°C.

c) Increased flexibility. In addition to allowing up to 25% of cellular offices, the building had to be divisible into units of block-by-block or even floor-by-floor in the event of being let.

d) Comfort that mixed mode could withstand the likely effects of climate change. The concern was with natural ventilation the higher the outside temperature the higher the inside if occupants were free to open windows during heat waves.

Further, experience at the previous building, the Barclaycard HQ, left some issues that were either not resolved on that building at the time or could be improved upon in the new one, e.g.

e) Draughts from trickle vents.
f) Allowing out of hours working in certain zones.
g) Over-warming of upper floors connected to the atrium.

The challenge to the design team was to resolve these issues within the constraints of an energy efficient design. The goal was to achieve an "Excellent" rating from BREEAM.

The Building

The site, shown in plan in figure 2, is steeply sloping, so the pond was sited at the bottom to benefit from natural drainage of the site. The plan was to construct the building in two phases to allow future expansion. The first phase was 10,000 m2 and the second 4,000 m2. It was considered impractical to build the cooling pond in two phases therefore it was sized initially to cater for both phases.

The building, shown in plan in figure 2, is a linear form with an east west main axis resulting in one long side facing north and the other facing south. Offices are located either side of a central atrium which runs from one end of the long axis to the other. The atrium is a key factor in naturally ventilating the building and providing a means of overnight cooling when external temperatures are low enough. The external facades of the building are designed to reflect the different exposures with a deeply recessed heavy façade on the south and light cladding on the north. Brises-soleil are installed on the south face where recesses do not provide adequate solar shading.

The ceiling is the exposed underside of the floor slabs. The floor-to-ceiling heights are generous, at 3350mm, by comparison with typical office buildings but they are an important feature in terms of maintaining thermal comfort at minimum energy use. The floor slabs are pre-cast units each 3m x 7.5m pre-cast concrete units each containing a single 110m long, 20mm polybutylene tube. There is a raised floor for the distribution of IT cables etc. and outdoor air when the mechanical ventilation is operating.

Based on experience at Barclaycard, the amount of opening window was reduced considerably but powered actuators are provided to allow occupants local control or override by the BMS when the building is either being naturally ventilated or cooled. In addition to the opening windows trickle vents are installed at both high and low level. The high level vents are permanently open and the low level controlled by hit and miss dampers. There were complaints of draughts at the Barclaycard building when the wind direction was from the north. The design of the trickle vents has been changed to direct the air away from occupants.

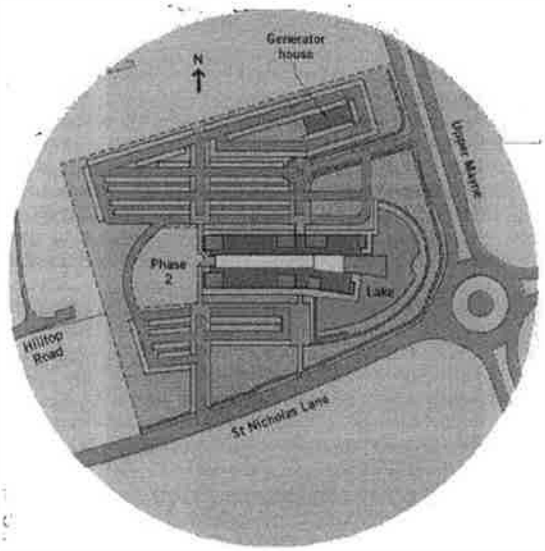

Figure 2. Site Plan

The Mechanical Systems

The mechanical systems are intended to compliment the passive design features of the building and should only be used when passive techniques are unable to maintain conditions in occupied spaces. They were selected to meet the performance required by the client's brief and operate for the minimum period of time at minimum energy use consistent with maintaining conditions. A key feature is the decentralisation of the plant and distribution systems to match the planning of the building. The objective being to only operate the minimum amount of plant necessary to maintain conditions in any zone calling for mechanical heating, cooling or ventilation rather than run an entire system and meet the consequential total transport energy demand to supply potentially a single zone. The building is shown in plan form in figure 3.

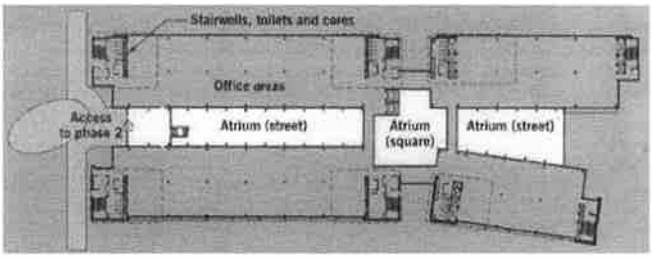

Figure 3. Plan of Building

Services from individual plant rooms are supplied to six zones each with three sub-zones (floors). Four of the plant rooms are identical and the other two have additional plant to handle out of hours loads and a planned kitchen. Each of the four basic plant-rooms houses:

a) A water cooled chiller
b) Heating boilers
c) Hot water storage calorifiers
d) Office ventilation units
e) Zone circulating pumps
f) Toilet extract fans

Naturally cooled water is drawn from the pond through a simple inverted pipe inlet (with a flange for cleaning) to a plate heat exchanger in a basement plant room and returned to the pond. A separate closed water circuit, on the building side of the heat exchanger, distributes cooling water to each plant room. It is circulated by individual single speed pumps to 18 floor zones from six plant rooms. When the temperature of the cooled water is too high to maintain conditions using natural cooling the mechanical chillers operate to reduce the temperature of water to the slabs. The cooling pond water is then used to absorb heat rejected from the condensers. The original intention was to use ammonia chillers but the additional cost of the safety equipment to comply with BS 4434:1995 and the HSE PM81 proved cost prohibitive. Consequently, R407c was used at little loss of efficiency.

Chilled Slabs

The concept of a chilled slab as a combined means of cooling and storing thermal energy has been developed by Meirhans (5). The basic principles are taking advantage of lower ambient temperatures overnight to accumulate low grade cooling energy and the cool radiant effect of chilled ceilings. The stored "coolth" is released gradually during the course of the day and cools the space by radiation and convection.

The slabs used by Meirhans are constructed from continuous circuits of plastic pipes buried in cast in-situ floor slabs. The ends of each plastic pipe circuit are extended outside and beneath the slab and connected to cooling water system pipes at high level. The cooling performance of these slabs, with pipes buried to a depth of 70mm above the soffit, is 27 W/m^2 using water, cooled overnight, to 19°C (6)

There are a number of differences between Mierhan's projects and this building.

- The heat gains are much higher, around twice as much, due to the density of occupation and office computers, photocopiers etc.
- Water-cooling is available from a cooling pond.
- The slab construction is pre-cast as opposed to cast in-situ.

The cooling power of a chilled slab is the same as a radiant chilled ceiling and is proportional to the surface temperature. Tests were carried out by BSRIA (4) to confirm the cooling power and the storage effect. The results from these tests confirmed the following:

- The slabs achieved a steady state cooling rate of 64 W/m^2 with the space maintained at 25°C, and chilled water flow and return at 13/16°C.
- 90 to 95% of cooling is from the lower surface (the upper surface is the bottom of the under-floor void)
- temperatures within the slab do not vary much, the standard deviation of internal temperatures was generally less than 0.3K
- the time lag between the pipe and the lower surface of the slab is consistent with published values.

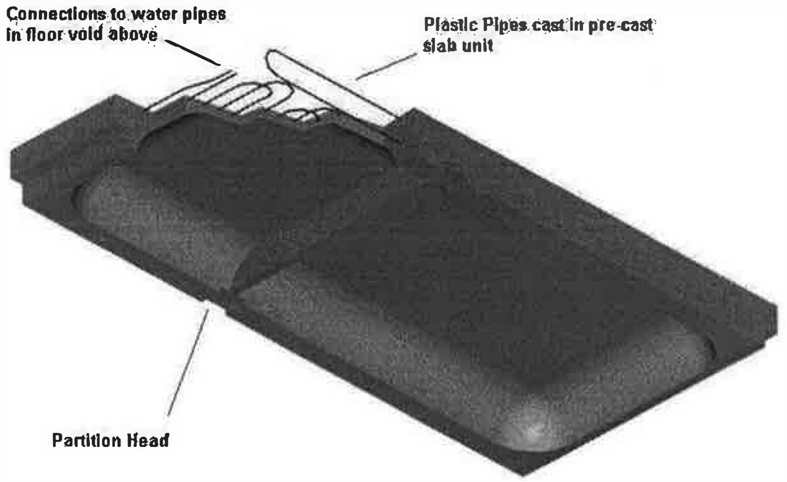

Figure 4. Cut away view of chilled slab viewed from underside.

The tests confirmed the slabs could provide adequate cooling to meet the brief for the proposed building and they were used to develop the design of the slab used in the construction. The design of the pre-cast slab actually used was more complex than the flat test slab as the architect introduced a profile around the edges (see figure 4). The pipe matrix was attached to the reinforcement bars to follow the profile and achieve the required area of cooling surface. The slabs were constructed in a pre-cast factory with the pipes pressurised during the concrete pouring. The pipes were pressure-tested after the slabs had cured. Connections were brought outside and above the slab such that they could be connected to a pipe circuit in a false floor above the space being cooled.

Control

The design goal for the BMS control system was to ensure the minimum energy necessary is used at any time to maintain the specified comfort conditions in the space. This meant ensuring the alternate modes of passive and mechanical must be controlled without wasting mechanical energy and avoiding the potential conflict between cooling the slabs by circulating water through interstitial pipes and cooling from the surface using overnight ventilation. The length of time to charge, i.e. cool a slab, had been determined from the BSRIA tests at between 3.5 and 4 hours and the time lag between circulating cooling water through the pipe and the effect being discernable at the surface takes around 30 minutes. The storage effect and the time lag needed to be included in the control logic. Further, there is the option to charge the slab continuously in proportion to the rate of cooling at the surface or charge intermittently by pulsing the circulating pump on and off.

The arrangement of sensors and control links are shown diagrammatically in figure 5.

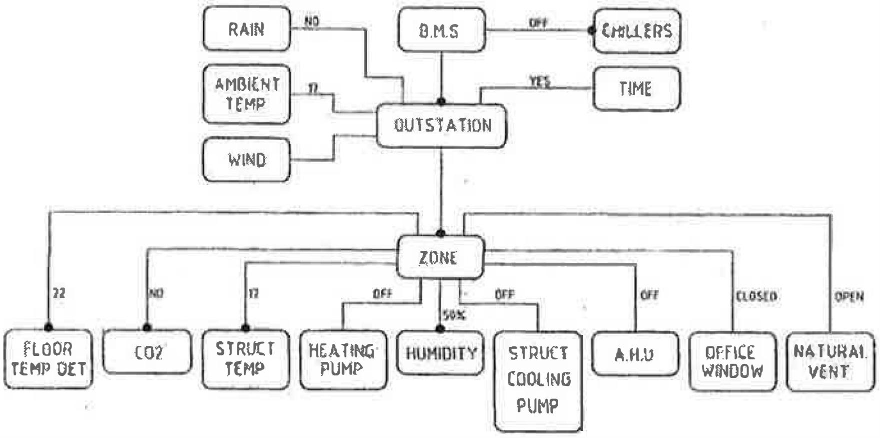

Figure 5. Simplified control diagram.

Progressively, in terms of energy use, cooling is provided by:

a) overnight ventilation,
b) overnight ventilation plus water cooling the slabs,
c) chilling the slabs,

depending on outside conditions and the recent thermal history of the slab. Separate plant provides cooling for continuous loads such as IT rooms.

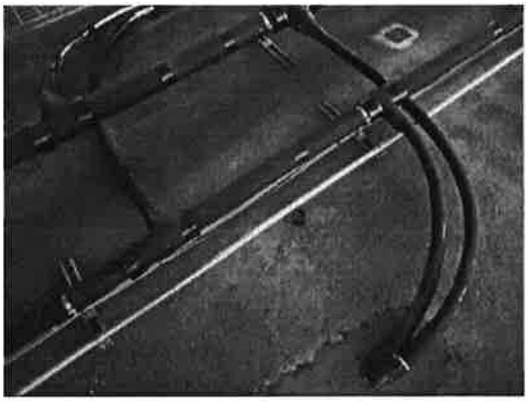

Figure 6. Below floor connections of slab to cooling water circuit

Installation

The pre-cast concrete slabs were constructed off-site including burying the pipe coils. The installation on site was no different to ordinary pre-cast slabs other than the size, 3m x 7.5m. Once the slabs were installed they were piped together and to the water-cooling circuit. (See figure 6.)

This resulted in a significant simplification of the building processes by comparison with an air-conditioned building or even one using chilled beams.

The decentralised plant rooms provided another positive improvement to the normal construction process. Central basement plant rooms were difficult to achieve because of limited space and the cost of excavation on the steeply sloping site. This led to the decision to consider roof plant similar to the Barclaycard building but include boilers and chillers in each plant room. If built in the conventional manner the plant-rooms could not have started until the building had been completed to roof levels. By pre-fabricating the plant-rooms, both the building and the plant-rooms could be constructed concurrently. Further the quality of plant-rooms produced in the factory is inevitably superior to those built on site for practical reasons and construction, testing and pre-commissioning could all take place in a clean internal environment beforehand. Obviously this reduces the time necessary on site for cleaning and commissioning.

The original idea of testing plant rooms at the factory and reducing the on-site testing and commissioning period was not achieved for the following reasons.

a) The Contractor resisted it because of the time that was needed to fill the systems and provide bypasses to represent the final installation.

b) The control system was a separate package. Had it been incorporated into the modular plant room package then electrical testing and control operational testing could have taken place in the factory.

Notwithstanding the above comments, the use of pre-fabricated modular plant rooms achieved a reduction in the construction programme time, flexibility for zoning and an improved product quality.

Commissioning

Commissioning of the heating and cooling pipe work systems was quick and achieved the specified flow rates. This is not surprising because both systems were piped in reverse return with no regulating valves on the system.

When the pre-cast concrete units were made in the factory, there was a requirement that there should be both flow and pressure tests. The pressure test was to maintain the operating pressure throughout the casting and curing period. The flow test was simply measuring the time it takes for a fixed quantity of water to pass from one end of the slab to the other. Having observed the way the pipe was installed on the steel reinforcement it was clear that either the pipe would kink because it was pulled beyond its minimum radius or it would maintain the proper cross-sectional area. There was unlikely to be any in between position so simply timing the flow from one end of the slab to the other was sufficient to see if the pipe had been kinked.

There was concern that the pre-cast slabs should not be tested at a higher pressure than working pressure in case it resulted in a gap between the cured concrete and the pipe outside wall at working pressure. After an hour of concrete curing the temperature generated by the process expanded the water volume in the pipe and increased the test pressure. It was therefore necessary to release water from the system to maintain a constant pressure and hopefully ensure good thermal continuity between the pipe and the concrete. Water flow through the slabs was verified using a thermal image camera and nine were found to have no flow. Fortunately these slabs were just valved closed. At final commissioning the flow rates through the slabs were all as anticipated.

The cooling pond on the Barclaycard project also acted as a sprinkler storage system consequently it was necessary to provide sluice gates and concrete intake chambers etc. In this pond there is a simple pipe, which turns down approximately 1.2metres below the surface with a restrictor at the bottom to ensure that nothing larger that the pipe work can enter. There is also a flange connector at the top to allow cleaning if ever needed. The discharge back to the lake is at the opposite side just below surface level and makes a pattern on the water that pleases the architect. This system commissioned well as there were no valves to balance.

Discussion

The application of interstitially cooled chilled slabs effectively turns conventional air conditioning inside out. In conventional systems air in the space is used as the transport medium to remove heat and maintain that same air at or close to the control condition. However the great majority of heat stored in most buildings is in the structure i.e. the walls and floors. For example, on a superficial basis per unit floor area a typical concrete building might have 3.0 m of air filled space below a concrete slab with a depth of 300mm. The thermal capacity i.e. mass times specific heat is 1,925.0 kJ/m^{3}K for concrete and 1.2 for air, a ratio of 1600:1. In buildings where the mass is closely coupled to the space the dominant thermal mass of the structure will effectively control the air and resultant temperature in the space. It appears to make sense to remove heat from the mass of the structure directly i.e. interstitially rather than to attempt to do it the other way round with the known difficulties in attempting to cool slabs from the outside with ventilation air.

In addition, close coupling of the thermal mass of the slab to the space provides stable thermal conditions due to the "thermal flywheel" effect.

The project was certified practically complete at the end of 1999 with some commissioning outstanding. This was completed in March 2000. Unfortunately, so far as "tweaking and fine tuning" the systems are concerned, there have been changes in the Client organisation which mean the original occupants are no longer going to occupy the building. It will be let to a tenant/s but in the meantime it is unoccupied. The design team look forward to the building being brought to life by being occupied and monitor the performance and will in due course publish the results.

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