Using fabric thermal storage to provide passive cooling

Studies at the Oxford Brookes University have shown that opportunities for improving a building's fabric thermal storage performance relate more to aspects of its configuration, control and ventilation strategy than the choice of structural system.

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A full set of the conference proceedings can be viewed on the Internet at: http://www.sustainable-steel.com

References

[1] Barnard N, 'Dynamic energy storage in the building fabric', *BSRIA Technical Report 9/94*, BSRIA, 1994.

[2] CIBSE *Guide A – Design data: Section A5: Thermal response of buildings*, CIBSE, 1986.

[3] Kendrick C C, *'The use of structural components to provide thermal storage and night cooling in a building at the University of East Anglia'*, MSc thesis, Cranfield, 1995.

[4] British Council for Offices, *'Draft specification for urban offices'*, BCO, 1994.

Further reading

CIBSE, *CIBSE Guide C – Reference data: Section C3: Heat transfer*, CIBSE, 1986.

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Using structural elements of a building as sinks to absorb heat conveyed by convection and radiation during occupied hours – followed by a period of overnight ventilative cooling – has been shown to be beneficial, both in terms of occupant comfort and overall energy use[1].

There has been a tendency to equate high levels of physical mass in the building structure with good passive thermal performance, but studies at the Oxford Brookes University show that other factors, such as control and ventilation strategies, must also be taken into account.

When using thermal mass to make thermal comfort comparisons between buildings, any analysis must take into account both the air temperature and the mean radiant temperature.

Exposed surfaces with high thermal mass could substantially reduce the mean radiant temperature in the space, and make a significant contribution to the resulting thermal comfort of the occupants, as heat can be radiated directly to the surrounding cooler surfaces.

Obviously, the greater the mass which is incorporated into the building fabric (for instance with thicker floor slabs), the more heat can be stored over an indefinite time scale.

However, buildings respond to diurnal temperature changes (an approximately sinusoidal cycle with a period of 24 h) and to daily solar and occupancy-related heat gains. Heat transfer is dominated by surface resistance, which limits the rate of energy exchange, and thermal storage can only continue for as long as temperature differentials allow.

There is thus a finite limit as to how much heat can be stored or discharged in the time allowed, and there must be a mass thickness beyond which there is no further storage capability to be gained when confined to a diurnal cycle.

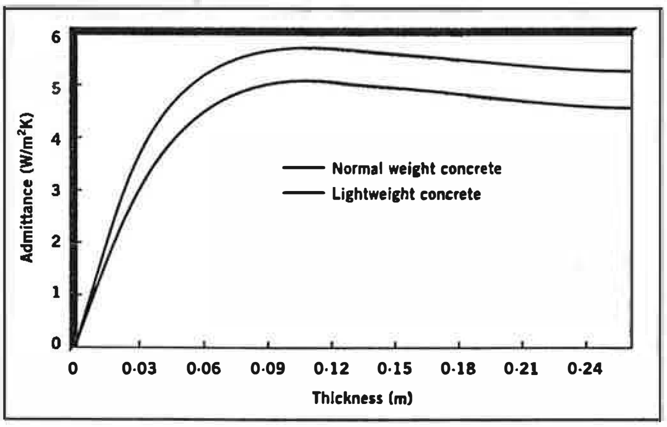

FIGURE 1: Measured thermal admittance of normal and lightweight concrete.

Thermal admittance

The concept of admittance was developed to provide a measure of the ability of a building to absorb and re-admit heat over a 24-h cycle[2]. It can be defined as 'the rate of heat flow between the internal surface of a construction and the space temperature for each degree swing in space temperature about its mean value', and is measured in W/m^{2}K.

The calculation of admittance for increasing thicknesses of concrete, using heat transfer coefficients expected in naturally ventilated buildings, shows that it reaches a maximum at a thickness of around 100 mm. This indicates that there would be little advantage in increasing the thickness of a construction beyond 100 mm, assuming that a constant 24-h temperature cycle applies.

It can be calculated that a thickness of just 75 mm will have an admittance of around 95% that of a 100 mm slab.

Lightweight concrete containing pulverized fly-ash is increasingly being used in steel-framed buildings to keep structural weight to a minimum. It has a density around 77% of that of normal weight material, and a thermal conductivity of just over half that of normal weight concrete.

Figure 1 compares the admittance of light and normal weight concrete. The graph shows that conductivity has less influence than might at first be expected, as a 45% reduction in this property results in a 10% reduction in maximum admittance.

The calculation of admittance for a slab of normal weight concrete at various values of convective heat transfer coefficient (h_c) shows that this parameter has a much greater influence than any properties of the material itself.

If the surface resistance to heat transfer can be overcome, much greater thermal penetration, larger admittance values and, hence, improved thermal storage can be achieved in the slab.

In practice, mechanical ventilation is required to achieve values of h_c over about 4 W/m^2K. The actual value of h_c depends upon the airflow rate, and the level of turbulence created in the airflow. The latter is a function of surface roughness and obstructions in the airflow path.

Ducting air through hollow cores in precast concrete slabs can achieve an overall value for h_c of approximately 9 W/m^2K, although the value is extremely variable and reaches a maximum at the abrupt change in direction between cores[3].

Underfloor ducting will enhance h_c to a lesser extent, as lower air velocities are reached in the larger plenum formed beneath a raised floor.

Recent tests at the Oxford Brookes University have shown that values of h_c over 30 W/m^2K can be approached by ducting supply air close to the slab surface beneath steel sheeting.

The law of diminishing returns applies to increasing the convective heat transfer coefficient beyond a value of 20 W/m^2K, with the increase in admittance becoming progressively less as the h_c is raised further.

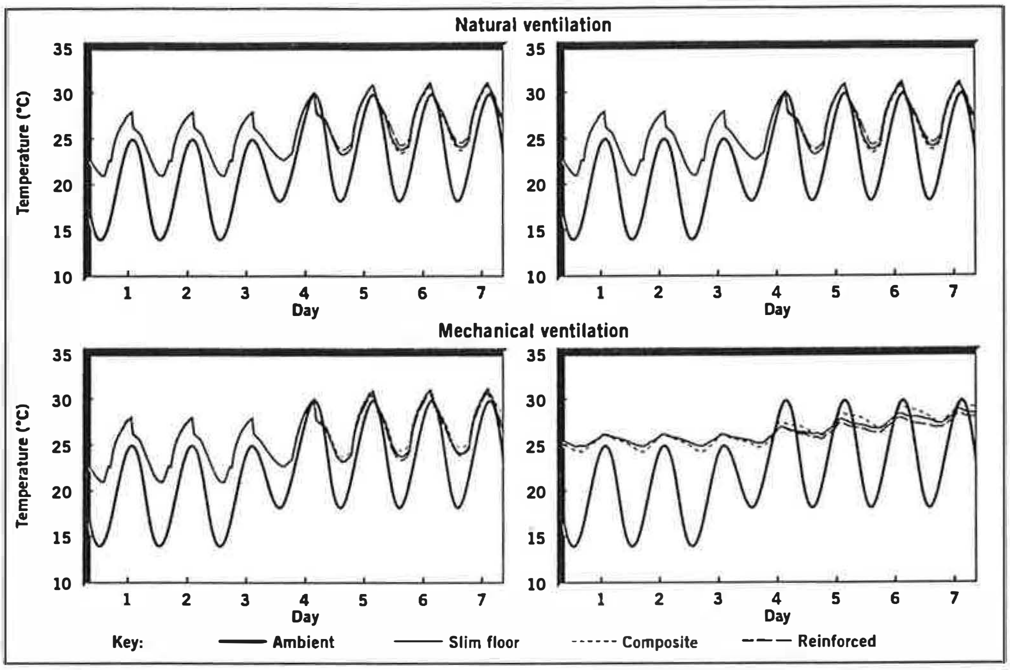

FIGURE 2: Predicted internal dry resultant temperatures (left) and exposed surface temperatures (right) for the test building.

Building simulation

The influence of such trends on the ability of different quantities of thermal mass to improve internal conditions is not so clear, and requires more sophisticated techniques to determine.

Dynamic thermal simulation provides a tool for such an analysis, and has been used to investigate conditions in a typical office building.

In order to compare the thermal response of steel and concrete-framed buildings with exposed thermal mass, researchers at the Oxford Brookes University have used a whole building simulation package to create a computer model of a typical commercial building. The package was set up to compare the thermal performance of three structural systems, namely:

☐ a slimfloor construction of steel beams and 200 mm-thick precast concrete slabs;

☐ a composite construction comprising steel framing and concrete slabs (120 mm thick) on a steel deck;

☐ a 300 mm-thick reinforced concrete flat slab construction.

The base test building is a typical speculative four-storey office development, with a plan dimension of 48 m by 13·5 m.

Internal loads in the building are taken from the British Council for Offices' *Draft specification for urban offices*[4], and applied for the occupied period of the working week.

The loads are as follows:

☐ occupancy: one person/14m^2 (100 W sensible, 40 W latent);

☐ lighting load: 12 W/m^2 sensible;

☐ equipment load: 15 W/m^2 sensible.

It was assumed that the underside of the floor slab was completely exposed for heat transfer in each case.

Each construction type was modelled using natural and mechanical ventilation. For natural ventilation, a daytime air change rate of 6 ac/h was assumed, with 2 ac/h at night. An air change rate of 6 ac/h – both day and night – was assumed for the mechanically ventilated options.

Both artificial and real weather data were used for the simulations. Artificial weather was used to obtain performance data for a repeated 24-h cycle of typical UK summer temperatures, and for investigating the response to a step increase in ambient temperature (an extreme case of temperature ramping).

The real weather data (Kew, 1964-1965) was applied to determine both energy consumption and the frequency of high temperatures for a typical year.

Using artificial weather data, figure 2 shows the predicted internal dry resultant temperature for the building using each construction system, with natural and mechanical ventilation respectively.

In the first three days of tests, when the diurnal ambient temperature cycle is repeated, there was very little difference in predicted dry resultant temperature for each construction, indicating that performance is comparable for the 24-h period.

A step increase in mean ambient temperature (but with the same swing) of 5 K was introduced between days three and four, representing an extreme change unlikely to be encountered in practice.

The differences in dry resultant temperature for each structural system are small, particularly when compared to the magnitude of the increase in ambient temperature.

The two graphs on the right of figure 2 show the exposed surface temperatures for the same seven-day test period. It can be seen that the heavier construction heats up more slowly than the lighter slab, having more thermal inertia as expected, but once again the differences are small.

Using real weather data, the predicted energy consumption was calculated for each structural system for natural and mechanical ventilation. Gas is used to provide space heating, and electricity is used for pumps in the heat distribution system, and to power fans. A small difference of 1-2% between the three construction types is predicted.

The tests showed little difference between the structural systems for the number of hours per annum above set temperatures in the occupied space. This reinforces the previous finding that the three slab constructions modelled result in similar thermal response in real applications where the 24-h temperature cycle predominates.

A much greater difference can be made by enhancing the heat transfer between the air and the slab by using direct mechanical ventilation over the slab surface.

It is surface resistance to heat transfer that is the limiting factor, rather than the thickness of the slab.