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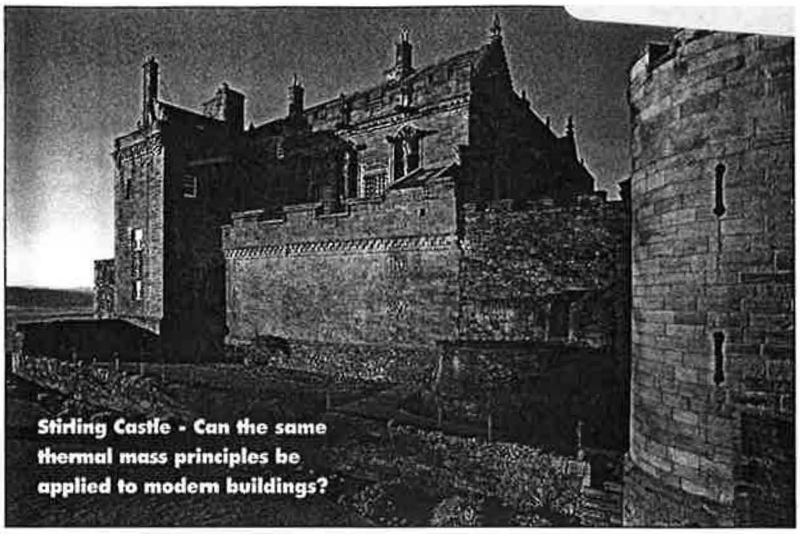
The belief that the addition of mass to a building will reduce its energy requirement is now widespread. Fiona Cousins and Bob Lang investigate how this principle, often observed in the coolness of cathedrals, castles and caves during summer, can be applied to modern buildings



Stirling Castle - Can the same thermal mass principles be applied to modern buildings?

Aspects of structure and thermal mass

BUILDINGS which have different uses also have different optimal thermal properties, but office buildings are considered a good example to study because they often illustrate an acute financial balance between construction cost and return from reduced bills for energy.

Anyone visiting a cathedral or castle at the peak of the summer will notice that the internal temperature is lower than the outside temperature.

During the winter a visit to a cathedral can be a much more miserable experience: it is likely to be draughty and cold, although warmer than outside. Heating bills for cathedrals and churches tend to be high.

> "A building with good thermal performance will generally be one where the solar gain is minimised"

Most modern buildings are neither castles nor cathedrals, but a similar definition of good thermal performance remains: Thermal performance for buildings is said to be good if the additional energy from an external source required to bring the space to a comfortable temperature is low. The thermal performance may also be described as good if the external thermal stimuli on the building result in low loads on the building services plant and acceptable temperatures.

GAINS

■ The relative length of the cooling and heating seasons for different buildings depends on their uses and construction types. Office buildings will have a shorter heating season than dwellings or cathedrals because their average internal heat gains are higher. In a typical naturally ventilated office with 100% double glazing and an internal gain of 35W/m2 , the internal heat gain will offset the heat loss at an external temperature of 0°C. Any heating will, therefore, be installed to prevent condensation damage when the building is not occupied over long periods, or to heat up zones of the building which might have lower internal gains than other areas served from the same systems.

The total heat gain depends on the solar gain. The amount of solar gain is determined by the fabric of the building, its shading, the material from which any internal surface on which the sun falls is made, as well as by the time of day.

A building with good thermal performance will generally be one where the solar gain is minimised. This is because solar loads are extremely time-dependent and are often much larger than the total of all of the other gains. The control of solar gain also frequently depends on the use of blinds which, if not operated automatically, are not a totally reliable shield. If buildings with low internal gains are operated correctly, then solar energy can be used to provide much useful heat in the winter, thus improving thermal performance. However, in order to simplify the current discussion, solar gain is treated as one of the stimuli to which the building responds rather than as an energy source, because this benefit is critically dependent on the occupants.

The key characteristics of a building with good thermal performance in the heating season is good insulation. Good insulation will reduce the amount of heat lost from the inside to the outside and hence the energy use. There are other factors which influence the comfort within the space and the energy use.

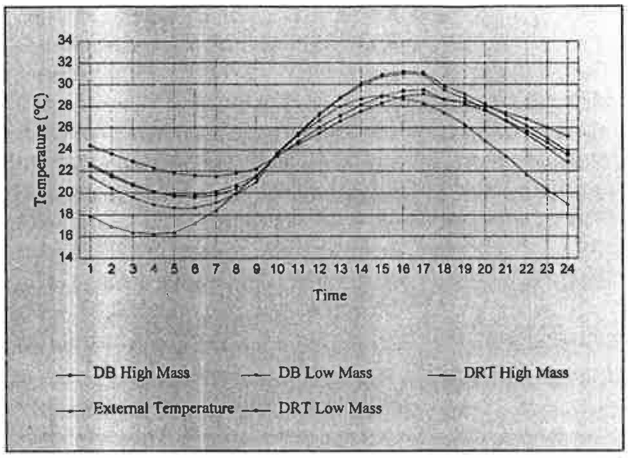


FIG 1
Variations of temperature with different thermal mass

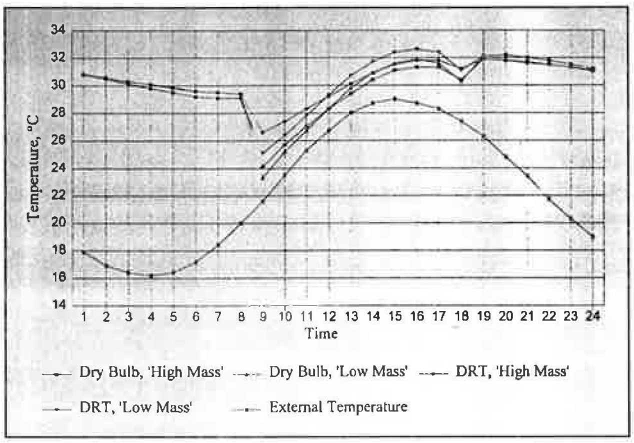


FIG 2
Variation of temperature with thermal mass, daytime ventilation

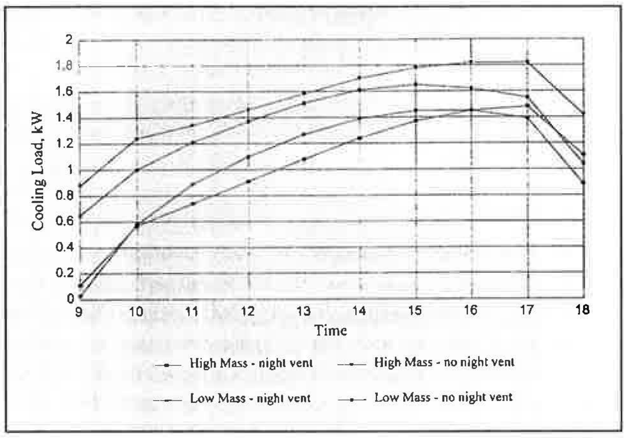


FIG 3
Variation of cooling load with thermal mass, daytime operation only

These include the length of time which it takes for a building to become warm after an unoccupied period and the feeling of warmth which comes from having carpeted rather than wood or concrete floors.

MATERIAL

■ The key characteristics for good thermal performance in the cooling season are less easy to identify than those of the heating period. In producing the low internal summer temperature of a cathedral, the most important property of the 'massive' construction is that it has a high thermal capacity. The specific thermal capacity of a material is the amount of energy required to raise a given mass of material by a given temperature. Buildings can have high thermal capacity either by having high mass or by being made from a material with high thermal capacity.

Stone is dense and has a high specific thermal capacity, as do concrete and water, while plasterboard and timber do not. Steel has a high density, but low specific thermal capacity. High mass, however, does not guarantee good thermal performance during the cooling season.

Before demonstrating the effect of the location of mass we need to define some temperatures. In an air-conditioned office the thermal performance can be measured by the amount of energy used to cool the building to a comfortable temperature. In a naturally ventilated building no energy is used and it is more appropriate to measure the thermal performance in terms of the level of comfort which can be achieved. For the purposes of this article, comfort will be defined in terms of temperature.

People exchange heat with their surroundings through convection to the air, conduction through their clothes and radiation between their clothes and the room surfaces. All these processes contribute to the temperature felt, and thus to the comfort of the person. The dry resultant temperature (DRT) is defined as the average of the air temperature and the area-weighted mean temperature of the surfaces which enclose the room. It is used as an approximate indicator of comfort. Comfort in an office may be achieved with a DRT between about 20°C and 26°C.

SURFACES

■ **Figure 1** shows the internal dry bulb temperatures for two offices, without air-conditioning, on a hot day in the UK. The two offices face south, are surrounded by other offices and have 20% glazing on the south face. The internal gain has been taken as 30W/m2, which is a moderate office load. Both rooms have concrete walls, ceiling and floor, but the one described as 'low mass' has a raised floor, a suspended ceiling and plasterboard studwork on the walls, while the one described as 'high mass' has exposed concrete surfaces. The graph shows that the temperature fluctuations in the room described as 'high mass' are much less than those in the other room.

In the 'high mass' room, the DRT is even more stable than the air temperature, in the 'low mass' room, the DRT is less stable than the air temperature. This is because the surface temperatures in the high mass room fluctuate much less.

Because both rooms contain the same amount of concrete, this graph shows that the presence of mass is not in itself enough to control temperature fluctuations. It is important that the thermal mass is in thermal contact with the air in the room. Comparing **Figure 1** and **Figure 2** emphasises this point. **Figure 1** shows the temperatures achieved

" High mass does not guarantee good thermal performance "

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if the office windows are left open overnight. This is frequently not possible because of security. **Figure 2** shows the temperatures achieved in the same two offices if the windows are closed overnight.

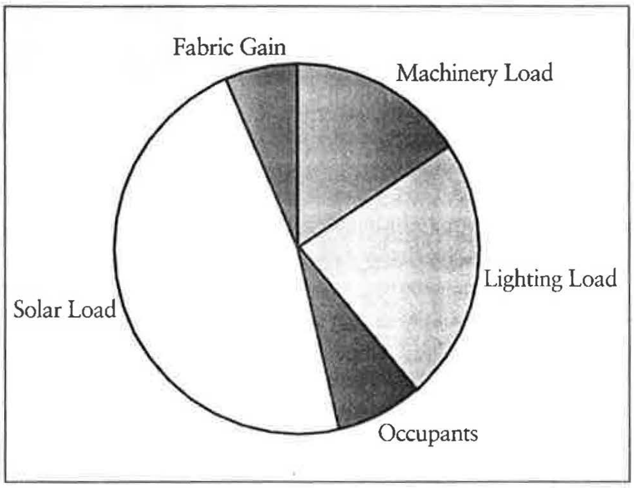
The lowest temperatures, which in this case are those closest to giving comfort, occur in the low mass room in the morning and the high mass room in the afternoon. Over a 24-hour cycle, the temperatures are much more constant and closer to the day-time average temperature than the overall average temperature than they are in **Figure 1**. This shows that in order to achieve the maximum benefit from the mass the temperature of the mass must be allowed to vary. To do this its surfaces need be able to interact with air whose temperature also varies. Heat flows can only take place where there are temperature differences.

Figure 3 is a graph of the sensible cooling load for the same offices as **Figures 1** and **2**, but in this case the rooms are air-conditioned to a temperature of 22°C.

Two scenarios are shown for each office, one in which the windows are open overnight, described as 'night vent', and one in which they are not. The windows are closed during the day while the rooms are air-conditioned. The high mass room with night time ventilation gives the lowest load, while the high mass room without night time ventilation gives the highest load. This is because the mass is only able to help reduce the load when its temperature is allowed to vary.

This shows that the ability to transfer heat from the mass to the air is more important than the presence of the mass. This can be described as having 'access' to the mass. Mass is not the same as thermal performance and, as shown by **Figure 3** can actually make the performance worse.

Buildings take time to respond to heat gains. The instantaneous load on the cooling plant or the temperature rise of the room air is not usually determined solely by the heat gain at that time but depends on the interactions between the heat sources and the building envelope and building surfaces. For example, electric fan heaters will heat air very quickly, giving a quick temperature rise. They have little effect on the surface temperatures in this time but raise the air temperature. Central heating hot water radiators take some time to heat the air in a room and need to be switched on before the space is required. This type of radiator heats both by radiation and convection. Air temperature rises are lower than for fan heaters although the instantaneous heat output may be the same. The conversion of heat gains into temperature differences is complex, because it is time-dependent and because surfaces react to conduction, convection and radiation in different, interrelated ways.



◄ **FIG 4 The proportion of loads from different sources**

Three factors, U-value, decrement factor and surface factor, are used to described the way in which the building modifies the radiant and conductive heat gains to give an instantaneous heat gain. The examples above show that convective gain, or gains to the air can happen almost instantaneously. There is therefore no modifying factor used for convective. A fourth factor, admittance, is used to describe how the heat gain is modified by the building to give a plant load or temperature rise. **Figure 5** shows the effect of the concrete thickness on these four factors, **figure 6** shows the effect of adding insulating finishes to the external surface of 100mm thick concrete and **figure 7** shows the effect of adding insulating finishes to the internal surface of 100mm thick concrete. Unlike the U value, which determines the steady state transmission through the building fabric, the three remaining factors are associated with variations from the mean. That is they determine the dynamic response of the space.

> "Mass can actually make the thermal performance worse"

The amount of heat conducted through external walls depends on the difference in temperature between the inside and the outside surface of the wall, the U-value, or conductivity, of the external wall and the decrement factor.

Taking the temperature difference between inside and outside first: A building surface which has the sun shining on it will be warmer than the outside air. The amount by which it is warmer depends on how much of the solar radiation it reflects. The difference between the air temperature and the surface temperature is called the 'sol-air increment'. White-painted buildings have a smaller sol-air increment than darker coloured ones, and this can help reduce the conduction gain.

The U-value is the conductivity of the construction. It is used to measure the insulation value of the construction. The lower the U-value the lower the conduction gain will be.

DECREMENT

■ The decrement factor is more complicated. The heat that falls on an external surface will either be re-radiated, in which case it does not affect comfort inside the building, or be conducted through it over a period of time. During this time the air temperature on the outside of the wall may fall below the highest temperature within the construction, and heat will be conducted both towards the inside and the outside. As a result, the heat that reaches the room will be a fraction of the heat that falls on the external surface, this fraction is measured using the decrement factor.

The time of the peak gain into the space occurs later than the time of the peak external surface temperature. The decrement factor therefore has a time lag associated with it.

In general, the lower the decrement factor and U-value, the lower the heat load on the room, and hence the better the thermal performance. **Figure 5** shows the variation of decrement factor and U-value with concrete thickness for exposed concrete surfaces. Both the U-value and the decrement factor decrease with increasing concrete thickness. Comparison of **figures 6 & 7** shows that the U-value does not depend on the order of the construction, but that the decrement factor is lower (more favourable) if the insulation is on the outside. The decrement factor therefore gives us some information about where mass should be located for good thermal performance.

The time lag associated with the decrement factor may improve thermal performance by displacing the heat gain from the time of peak external temperature or solar gain to a time of lower gain. In theory this may allow warmer temperatures to be maintained in the evening; in practice this is difficult to achieve. When the walls are very thick, as in a castle, the delay between the peak external temperature and the peak internal heat gain can be very long. **Figure 9** shows the U-value and decrement factor for super-thick constructions. In practice, similar results can be achieved by insulation.

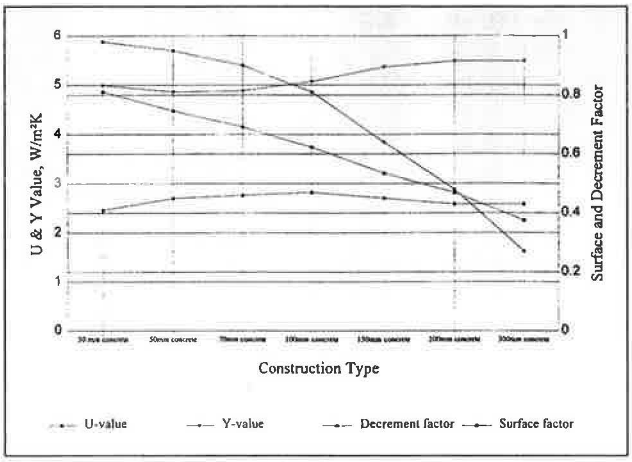
The surface finish influences all of the gains to the space which act through radiation. Any radiation which falls on the internal surface will be absorbed, reflected or conducted away. Absorbed heat will cause the temperature of the surface to rise and this heat will then be transferred to the room air through convection. These processes take time, and the peak heat gain to the room air will be less than the peak radiation heat gain to the room, and will occur after a time delay. The ratio between the peak solar radiation and the peak load on the system is measured using the 'surface' factor. The lower the surface factor the better the thermal performance in the cooling season. The delay can also be used to shift the peak internal load away from the time of peak external temperature.

SURFACE

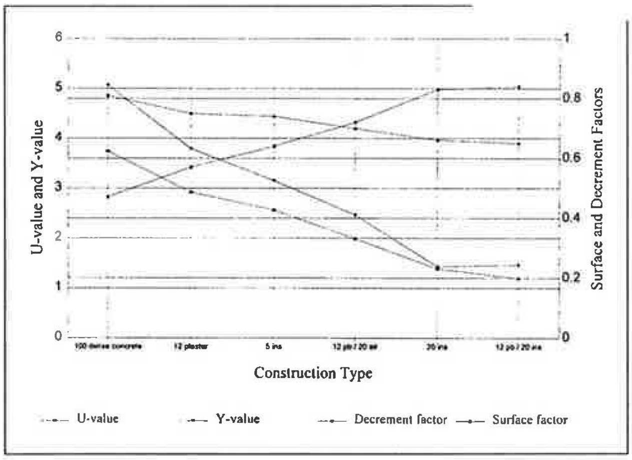
■ **Figure 5** shows that the surface factor is almost independent of the thickness of the concrete. Figures 6 and 7 show that the more insulated from the room the concrete is, the higher the surface factor. Where the insulation is placed on the inside of the concrete, the concrete has virtually no effect.

Admittance is used to measure the "rate of heat flow between the internal surface of the construction and the space temperature for each degree swing in space temperature about its mean value" (*CIBSE Guide A, 1986*).

This factor describes the interaction between the surfaces, which have been warmed by the radiant and conductive heat sources, and the air. Admittances are calculated for each surface type, the admittance of the space is the area-weighted average of these values. If the total admittance is high, the temperature change resulting from the change in the load is low, this is therefore a desired property in a cooled room. Admittance depends on the area of the different constructions. The total admittance may be increased by enlarging the surface area of high admittance surfaces. Admittance could be described as measuring the level of access between the space and the thermal mass.



◄ **FIG 5 Properties of concrete constructions**



► **FIG 6 Variation of factors with internal insulation**

Figure 5 shows that the admittance of concrete is almost independent of its thickness. Figures 6 and 7 show that insulating the concrete on the outside improves the admittance, but that insulating the concrete on the inside reduces the admittance drastically. As with the decrement factor and surface factor, the way in which the materials are arranged within the construction is important.

Standard values of all these factors are related to 24-hour cycles, which is realistic for most office environments. Figure 8 shows the effect of increasing the time over which temperature variations take place.

The results given in **figures 1, 2 and 3**, together with the thermal factors described provide some guidelines for how and where to include mass in buildings.

The U-value, decrement factor and surface factors should generally be low and the admittance should be high. Surfaces which have these properties are externally insulated concrete, brick or block, and are generally described as having a high thermal mass. However the results in **figure 3** show that there is no thermal advantage in having surfaces like this if they are unable to vary in temperature, and thereby influence the room air temperature. If there is no possibility of the temperature varying overnight, because the building has to be sealed then it is actually an advantage to have loss-mass surfaces, such as plasterboard partitions, raised floors or suspended ceilings. Covering high-mass surfaces with loss-mass finishes changes their performance so that they act as loss-mass constructions. Such finishes might be curtains, pinboards, or part-height partitions, such as those common in open plan offices.

Assuming that the temperature of the mass can be allowed to vary, the location of that mass within the room is still important. The surface factor is important in reducing the solar gain, and so high mass surfaces should be placed

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where the sunlight is going to fall. This would be the floor in open plan offices except that a large part of the floor is usually covered by furniture. There are no partitions in cellular offices so the only remaining surface is the ceiling. In cellular offices the sunlight will frequently fall on the partitions, so the solar load could be reduced by using block partitions.

Figure 4 shows that the most significant loads in a typical office are due to the solar gain and lights, with the fabric gain forming a very small part of the load. The critical factors are therefore the admittance and the surface factor, both of which are almost constant thicknesses of greater than 100mm. There is therefore only limited advantage in increasing the thickness of the concrete beyond 100mm in spaces which are subject to 24 hour cycles of temperature variation. Castles and cathedrals are not forced to have 24-hour temperature variations and therefore benefit from the additional thickness.

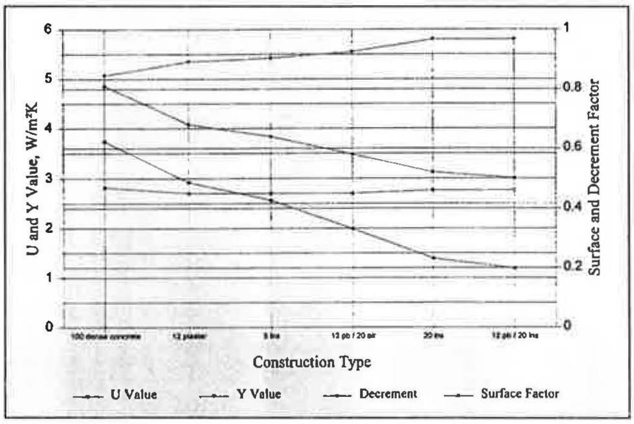

FIG 7 Properties of concrete with different external surface finishes

From calculation it becomes clear that admittance has by far the greatest effect on plant load. High admittance surfaces on the floor and ceiling will help to reduce the cooling load. This is how ceilings, and floors which do not have sunlight falling on them, can help to reduce the cooling load.

If admittance is considered as a measure of access to the thermal mass then it should be noted that there are other ways, such as passing air through holes in the slab, which can increase the effective admittance or access to mass. Some of these methods are described in BSRIA Technical Report 9/94.

Office buildings in the United Kingdom are frequently constructed using a steel or concrete frame. In the case of steel frames the floors are often provided using thin composite floor slabs formed from metal deck and, often, lightweight concrete.

Concrete-framed buildings generally have flat-slab or beam and slab concrete floors. Steel buildings are generally less heavy than their concrete counterparts.

The distribution of mass within a typical office building can vary considerably between elements that are structural and those that are fabric or finishes. Structure, partitions and finishes alone may weigh between 150kg/m3 and 250kg/m3 of the total building mass. Not all of this mass is accessible for thermal capacity since much of the structure is hidden behind cladding, false floors and ceilings which act as insulation. For the mass to be exploited as a climate moderator, it requires particular design decisions to be taken about how much the structure is exposed and the surface area available for heat transfer.

Partitions contribute a significant component to the overall mass of a building; ranging from about 50kg/m2 to 150kg/m2 (or more) of developed floor area depending on the choice of construction. When partitions are present they form one of the most significant areas of exposed thermal mass within the building.

In the absence of partitions, the floor and ceiling construction consistently provides the best opportunity for exploiting mass and the potential of thermal capacity. It has already been demonstrated that only the outside 100mm or so of a concrete mass is effective on the temperature cycles and usage profile associated with a modern office.

To supply a floor construction grossly in excess of this, solely for reasons of thermal capacity, is not necessary. The choice of structural form is therefore not limited by floor construction.

Instead, the issue translates to one of enabling access to the mass rather than providing a structure that is artificially heavy beyond what is required for normal levels of structural efficiency.

CONCLUSIONS

■ In offices the thermal characteristics which reduce the energy use the most are those which tend to reduce the cooling load. This is because offices have high internal heat gains which are a result of their functions as an office. The thermal characteristics which reduce the cooling load are similar to those found in extremely heavy-weight buildings such as cathedrals, but there are critical differences between the frequency and size of the heat loads imposed on cathedrals when compared to those imposed on offices.

For open offices the surfaces which are most readily available for exploitng thermal mass are the floor and the ceiling, in closed offices the partitions are also available. These surfaces are also often used to distribute essential services such as electricity, air and water throughout the building so making it difficult to access them for thermal capacity. Partition surfaces may also be covered by display material or acoustic absorption materials which significantly limit heat transfer between the mass of the surface and the room air. Some offices are so highly serviced that it is not practical to conisder either an exposed floor or ceiling, in which case thermal mass cannot be used to control temperature without running ventilation through the material directly.

COSTS

■ To exploit thermal mass, the choice of structural system need not be limited to any one particular material to the exclusion of all others. Given that the thermal mass is accessible for heat transfer within the building and it possesses appropriate physical properties, then the structure may undergo a process of optimisation in the usual manner.
Disproportionately heavy construction can be avoided. Additional capital costs associated with structure, and in excess of the minimum required for solely structural reasons, need not be added.

Improving the thermal performance of a building requires that all of the factors which influence that performance are considered together.

A structure need not be extraordinarily massive to exploit thermal capacity, but for mass to be effective it has to be accessible for heat transfer.

For normal occupancy patterns, 100mm of concrete slab will deliver the desired performance. ■

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