Buildings for extreme environments

Tropical

CIBSE

Contents

3 Building design, construction and materials

3.1 General

In all but the most severe tropical climates, outdoor temperatures and conditions are likely to be within comfort ranges for a large proportion of the year. There is likely to be no heating demand, except at high elevations, and cooling demand will be highly influenced by building design and form.

Thus, tropical regions have the potential to apply radically different design strategies, depending on the design team's experience and the users' requirements. Naturally ventilated buildings should seek to maximise thermal exchange with the outdoor environment. Air conditioned buildings may minimise this exchange and mixed mode buildings will have characteristics of both. Climatic characteristics will have a strong influence on the design strategies adopted. Broadly speaking, tropical climates can be grouped into hot-humid and warm-humid regions, each of which will benefit from different design techniques.

Common characteristics of all buildings will include protection of the building fabric from direct and diffuse solar radiation. This could include the use of high emissivity paint or detached shading on external surfaces as well as large overhangs, direct shading of fenestration and the use of vegetation for cover.

Key design decisions will involve the building form and orientation, internal layout, façade, ventilation openings, mechanical systems and control strategies. In this context, it is vital that the architectural and engineering design be closely aligned, with a shared vision of how the building should perform and respond to its environment.

3.2 Building thermal performance and thermal response

Every building is unique and, in terms of each building's responses to the outside environment, can be thought of as a 'low-pass filter'. Buildings do not respond to outdoor or indoor fluctuations instantaneously; their response is determined by outdoor weather conditions, the building envelope (i.e. wall, fenestration and roof systems), internal loads such as occupants and equipment, and building systems such as electric lighting, heating, ventilation and air conditioning. Thermal response, or thermal lag, describes the time taken by a building to respond to

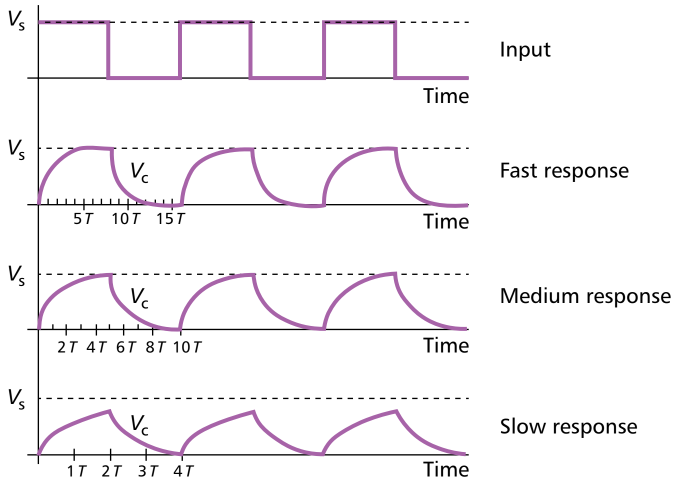


Figure 66 Building thermal response patterns

transient conditions. In this sense, it could be considered analogous to an electric resistor–capacitor circuit. A building envelope with high thermal capacity and thermal mass will take more time to respond, whilst a building envelope with low thermal capacity will respond to changing outdoor and indoor conditions more rapidly. Figure 66 explains this phenomenon visually. With the analogy to the electrical resistance and capacitance circuit, the time constant $T = R\,C$ is the time for V_c to rise to V_s.

The thermal performance of a building is a term used to describe the properties of a building that help to maintain the desired internal conditions, especially thermal comfort conditions for occupants. Desired conditions can be achieved by using 'active' or 'passive' means. Active buildings use mechanical systems, and hence energy, to attain the desired conditions, whereas passive buildings often attain the desired conditions with lower energy consumption. In the tropical context the deployment of passive and/or active strategies depends upon outdoor context of building, indoor heat generating conditions and building usage. Buildings meant to operate passively in 'naturally ventilated mode' will have different sets of design and construction criteria to buildings intended to be operated with help of mechanical cooling system.

The thermal response of a building is prioritised when a building is designed to operate in natural ventilation (NV) mode throughout the year. It also plays a major role when a building is designed to operate in temporal or mixed mode. Mixed mode (MM) buildings are designed to switch between NV operation and full mechanical cooling during various times of the day and year. MM building design should address both the thermal response and thermal performance of a building at same point in time. However, this may prove challenging in tropical climates. A focus on achieving better thermal performance of a building should be a priority when designing buildings to operate in air conditioned (AC) mode throughout the year. These are often sealed buildings, which are designed to have less interaction with the outside environment. However, this is likely to be affected by the cultural values of the occupants regarding what constitutes a desirable building or a good environment.

Thermal comfort conditions can be achieved in most AC buildings, irrespective of the architectural design, at the cost of large cooling plant and high energy consumption, although a good AC design will seek to minimise this. In order to achieve thermal comfort in MM or NV buildings, it is crucial for the architecture to be aligned with the engineering design and a clear understanding of how the building will operate.

3.3 Design strategies

3.3.1 Building operation mode

The choice of building operation mode depends upon the owner and the design team, and will have a significant impact on all phases of the building design and operation.

Designers should make a conscious decision before adopting any specific operation mode, whether AC, MM or NV, depending upon the geographical context of building and use of building. Key characteristics of the local climate should be well understood before the final selection of the operation mode. It is important to note that tropical climates offer ample possibility to design buildings for NV and MM operation.

One key aspect of the building operation mode is the selection of the comfort models to be used. In particular, naturally ventilated buildings that consider adaptive comfort models can be designed for wider temperature ranges than centrally controlled, air conditioned buildings. Section 2.1 of this guide describes indoor thermal comfort models in more detail.

Mixed mode operation can refer to buildings that operate in natural ventilation and air conditioned modes (*a*) in the same areas at the same time (concurrent), (*b*) in the same space at different times (change-over), or (*c*) in different areas of the building at the same time (zoned). Well designed systems often operate on a change-over principle, but careful specification of the control systems is crucial.

Many existing buildings in tropical areas were built before central air conditioning systems became common, and were later retrofitted with small direct expansion cooling systems to meet higher comfort expectations. Many buildings, both new and old, function in mixed mode without having been explicitly designed this way — for example, buildings with 'split' air conditioning systems that have operable windows and no direct outdoor air supply. In terms of energy consumption, the greatest performance risk is likely to come from buildings that were designed for natural ventilation and adaptive comfort models (high level of ventilation and interaction with the outdoor environment), but later retrofitted with air conditioning systems set to achieve low indoor temperatures (i.e. traditional comfort models).

It is common to see buildings that cool only certain rooms or critical areas. For example, a university building may cool only those classrooms with high density occupation and/or high internal loads. For office buildings, the high internal loads and demanding comfort requirements mean that they are rarely designed for full natural ventilation, and prestige offices ('AA' or 'AAA' classification) will nearly always operate in full AC mode.

3.3.2 Surface area

In designing for the operation modes described above, the floor-to-volume and floor-to-exposed envelope area ratios need to be considered, see Figure 67.

The ratio of exposed surface area to volume is an important factor in gaining an understanding of building's behaviour. In hotter climates it will be beneficial to minimise this ratio, whilst in warm-humid climates (predominant in tropical areas), higher surface-to-volume ratios may be beneficial for providing highly ventilated spaces However, in this case, selection of material and construction types should consider rapid heat dissipation.

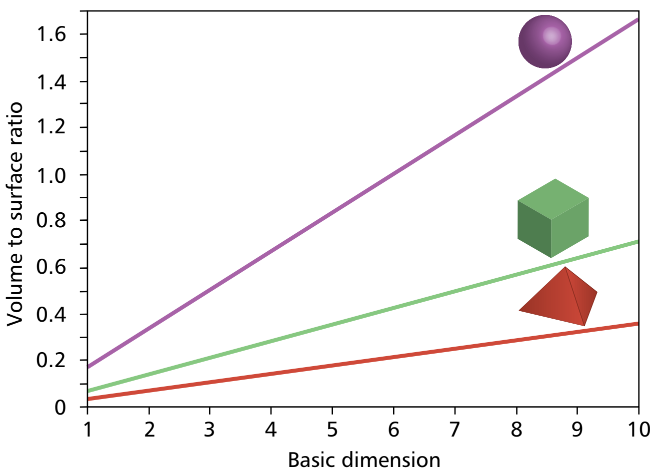


Figure 67 Volume-to-surface ratio of various shapes

A high ratio of envelope area to floor area would be characteristic of NV or MM buildings, which seek to maximise thermal exchange with the environment when external temperatures are not critical. A fully AC building will typically be designed to minimise the envelope area, as it seeks to reduce thermal exchange with the environment. A large floor plate in contemporary non-residential buildings is often associated with large internal loads. For buildings with heavy internal loads, due to high density of occupants and a high density of equipment having a high radiant fraction, or where buildings have extended operation hours, designers often opt to design for full AC operation. In tropical climates, dehumidification of the indoor environment becomes equally important as maintaining suitable temperature — in other words, the latent fraction of the load on the air conditioning system is highly significant.

3.3.3 Thermal mass

As mentioned above, tropical climates can be broadly divided into warm-humid and hot-humid climates. Both climate types have periods of mild temperatures during the year. During this time it is desirable that the thermal response of the building is similar to the external climatic conditions, either fluctuating with the outdoor conditions or staying at diurnal average temperatures (when peak daytime temperatures are too close to or above comfort levels). In other words, tropical climates offer the opportunity to operate buildings in NV mode, where indoor temperatures will fluctuate with outdoor temperatures subject to a certain thermal lag depending upon thermal response of the building. Thermal lag is a delay in stored heat being released from the thermal mass of the building envelope as outdoor ambient air temperature falls, see Figure 68. The thermal lag of a building depends upon both the heat capacity and the thermal conductivity of the building envelope. This is also known as the 'thermal inertia' of a building.

Not all tropical buildings require high thermal mass, and it is often appropriate to design buildings with relatively low mass in tropical areas. The functional purpose and real impact of thermal mass in a building should be carefully considered in the early stages of design.

When building indoor temperatures are 'floating' with outdoor conditions, high rates of air change are required to dissipate internal gains. Where buildings aim to maintain diurnal average temperatures, natural ventilation is still desirable but the ventilation rate must be controlled in order to maximise the use of the thermal capacity of the building structure.

Even when the external temperatures are well inside the comfort zone, the thermal capacity of a building can be important for absorbing internal gains. This is especially the case in non-residential buildings where the impact of internal gains can be much more significant than the external climate. (This is often the case with office buildings in warm-humid climates.) Nevertheless, in using thermal mass as a passive cooling strategy for daytime occupation, it is important to consider that the mass has to be cooled at some point. This can be done by allowing cool outdoor air to pass through the building during the night. This strategy is known as 'night cooling' and works well in regions with significant diurnal temperature swings (8 K is sufficient). Allowing buildings to operate in NV mode can be the right strategy when the outdoors is favourably cool. In warm-humid climates (where external temperatures are often within comfort ranges), thermal mass can be used in parallel with natural ventilation, working together in the removal of internal gains. Weather analysis is important to determine comfortable operational hours.

As can be seen in Figure 69, the operational comfort zone for naturally ventilated spaces in Chennai is between 23 °C and 28 °C. The most comfortable months in this climate would be September to December, while January would be quite cold and

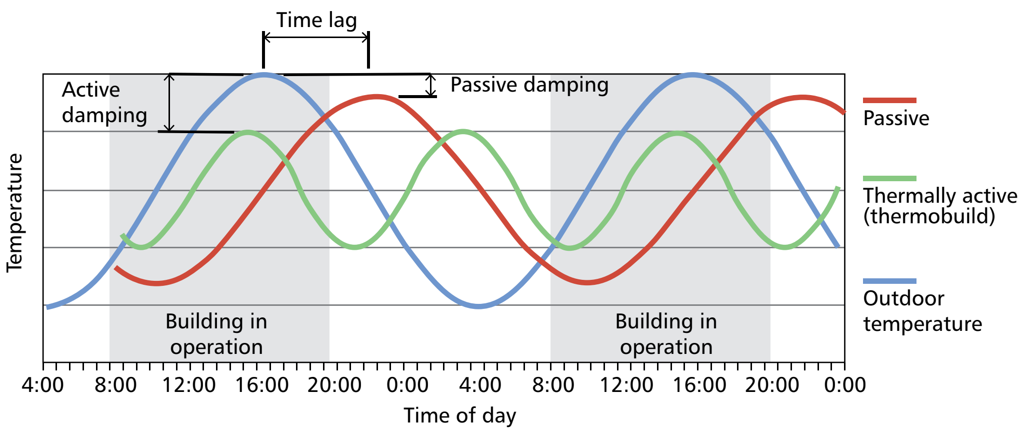


Figure 68 Thermal mass effect on buildings

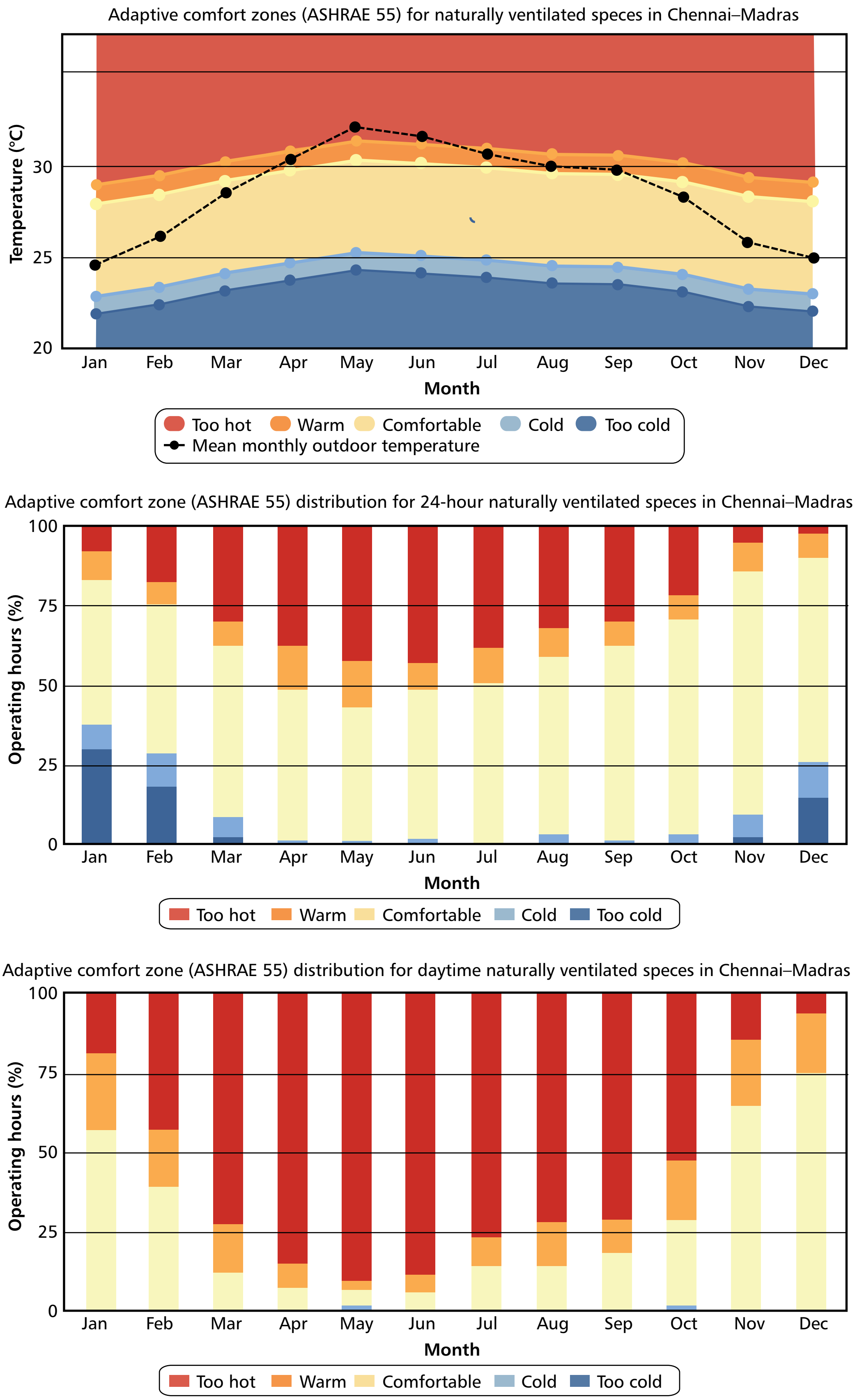


Figure 69 Adaptive comfort zones

Source: Comfort and Weather Analysis Tool at http://www.carbse.org/resource/tools

May too hot, as mentioned in chapter 1. Allowing office buildings to operate in natural ventilation mode during these comfortable months would be favourable, as the outside air would be well cooled and thus help in the removal of internal gains.

On the other hand, for buildings with high internal loads in warm humid climates, it might be more effective to detach the internal environments and the use of thermal mass from natural ventilation during the occupied hours and open the building again at night, after the occupation hours, to be cooled by night time ventilation, when the external temperatures tend to drop. In such conditions adoption of thermal insulation and thermal mass at the same place in the building is a design strategy that should be investigated. However, this is challenging exercise and is likely to require detailed thermal modelling to confirm its effectiveness.

Balanced deployment of insulation will not allow outdoor heat to ingress inside during harsh external conditions, which normally occur during the day. During this time the building should be treated as a sealed building with treated outdoor air, or should operate in full AC mode. When outdoor conditions become favourable, the building should be operated in NV mode. At this time thermal mass of the building will start storing 'coolth'. Subsequently this coolth will come into action when the outdoor temperature increases.

Having exposed thermal mass in the building can help not only the heat absorption but also the perception of comfort. This is due to the effect of radiant temperatures of the materials providing the thermal mass, which should be lower than the air temperatures. This effect will be greatest when the thermal mass is applied on the walls and ceiling, as it allows heat exchange with the body and head.

Even in hotter climates and fully air conditioned buildings, insulation of the building envelope may have negative implications for the daily thermal performance of the building, as it blocks possible heat losses during the night. Many urban buildings are not able to open windows and take advantage of cool outdoor air at night, due to security concerns, dirt accumulation or pollution entering the indoor spaces. Security concerns can be managed by safety grills, but to avoid dirt and pollution it may be necessary to rely on innovative contextual solutions. Sometime gable windows or dormer windows will provide ventilation. In certain parts of India, traditionally people have practiced having skirting to ceiling height windows with three divisions (see Figure 70). Depending upon time of the day and requirements for light and ventilation, occupants open the various sections of the windows.

In these cases, uninsulated building envelopes help to reject heat built up during the daytime. Insulation will only contribute to building performance and reduction in energy consumption when stored heat can be rejected without using energy. Thermal modelling analysis has to be applied to select an optimal strategy.

Figure 70 Traditional Indian windows
Source: courtesy of Chinmay Patel, Ahmedabad

In all of the design cases cited above, the building control strategies should be explicitly laid out, as they will be key to the successful operation of the building.

3.3.4 Ventilation

High ventilation rates, through natural or mechanical ventilation, can be effective at removing internal gains and, in the case of warm and humid climates, may also provide comfort cooling (as explained in chapter 2). For that purpose, it is important that the air flow passes through the body of occupants, at a useful height level within the internal spaces. This requirement has direct implications upon the design of windows and ventilation grilles used to direct air flow inside the building. As described above, the ventilation strategy must be considered in parallel with the intended mode of operation, the building mass and the façade design.

In hot-humid climates, even in passive buildings, in order to control the rise of internal temperatures it could be necessary to decouple the building from natural ventilation at certain periods, as described in section 3.3.3 above.

In warm-humid climates, although natural ventilation is desirable for most of the occupied time, it is important to provide users' control over the ventilation rates to avoid discomfort at certain times of the day and periods of the year, when external temperatures could be outside comfort ranges.

A more detailed description of natural ventilation strategies and techniques for tropical climates is given in chapter 5.

3.4 Material selection and construction methods

3.4.1 Opaque envelope and thermal mass

According to the principles of environmental design, buildings designed for tropical climates should aim to minimise heat gains and maximise heat losses. The building gains heat from external sources through conduction, radiation and convection — the intensities of these heat gains are defined by the building envelope design. (Note that as mentioned in section 3.3, internal loads may dominate in commercial buildings, especially in technology-packed modern offices, with large floor plates.) Heat gains from conduction may be reduced by lowering the *U*-value (i.e. heat transfer coefficient ($W/m^2 \cdot K$)), see Figure 71, but insulation should be used with care as it may reduce the building's ability to reject heat at night. Radiation gains can be reduced by effective shading and the use of finishes with high solar and infrared reflectivity. Convection is beneficial in tropical climates if ventilation is controlled to maximise air flow rates when external temperatures are within comfortable ranges, and minimise air flow rates during extreme high temperatures. By designing with the climate in this way it is possible to minimise, or in some cases completely eliminate, the dependency on energy consuming comfort systems inside buildings.

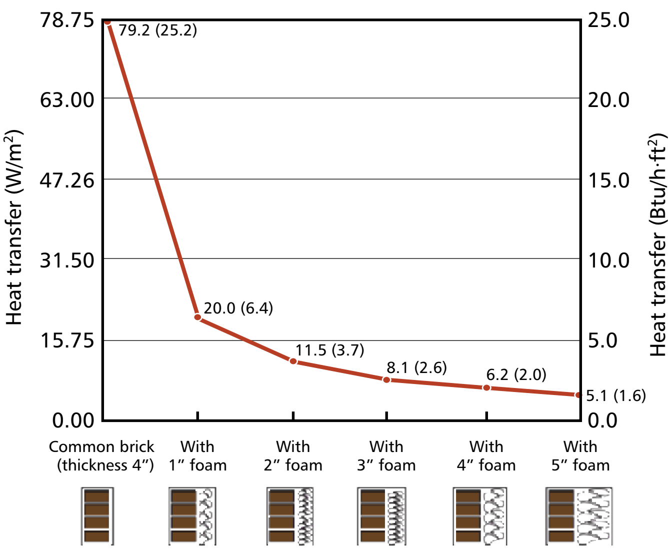


Figure 71 Heat flow through insulation

Source: Boonyatikarn and Buranakarn (2006)

As described in sections 3.2 and 3.3, the building envelope should have a good thermal response if it is intended to operate in NV or MM mode. Thus, in tropical climates with low diurnal temperature variation, high thermal capacity and specific heat may not be advantageous. Lightweight construction (with low thermal mass) in tropical climates can respond very quickly to available cool air with reasonable air velocity, cooling the building quickly when the outdoor temperature drops. However, the very high conductivity may not be able to create a significant thermal lag effect; the designers should carefully judge whether this will be required.

Where thermal mass is desired, fired clay brick, stone and mud are some of the traditional materials that may be used effectively. In recent times, materials containing phase change materials have shown promising results achieving a thermal mass effect, see Figure 72. Placement of phase change material inside wall constriction does help. Building orientation and placement of phase change material in strategic locations also can help to optimise material usage.

In less harsh climates, heat losses through conduction (especially during the night, applying reasonably high *U*-values) may contribute to the energy performance of the active cooling systems, by providing additional heat rejection capacity for both air conditioned and naturally ventilated buildings. This is because often in warm-humid climates, external temperatures can easily be close to the desired internal air temperatures (when accepting a comfort zone base on a model of adaptive comfort, as discussed in chapter 1), so higher levels of insulation, such as the ones applied in temperate, cold and even hot dry climates, are often not desirable. In fact, even moderate insulation levels can be shown to reduce the performance of buildings in many cases.

3.4.2 Glazing and fenestration

Where walls have larger areas of fenestration, higher natural ventilation rates for heat removal and comfort may be possible. However, large areas of glazing can also introduce significant thermal loads in the form of direct and diffuse solar radiation into the space.

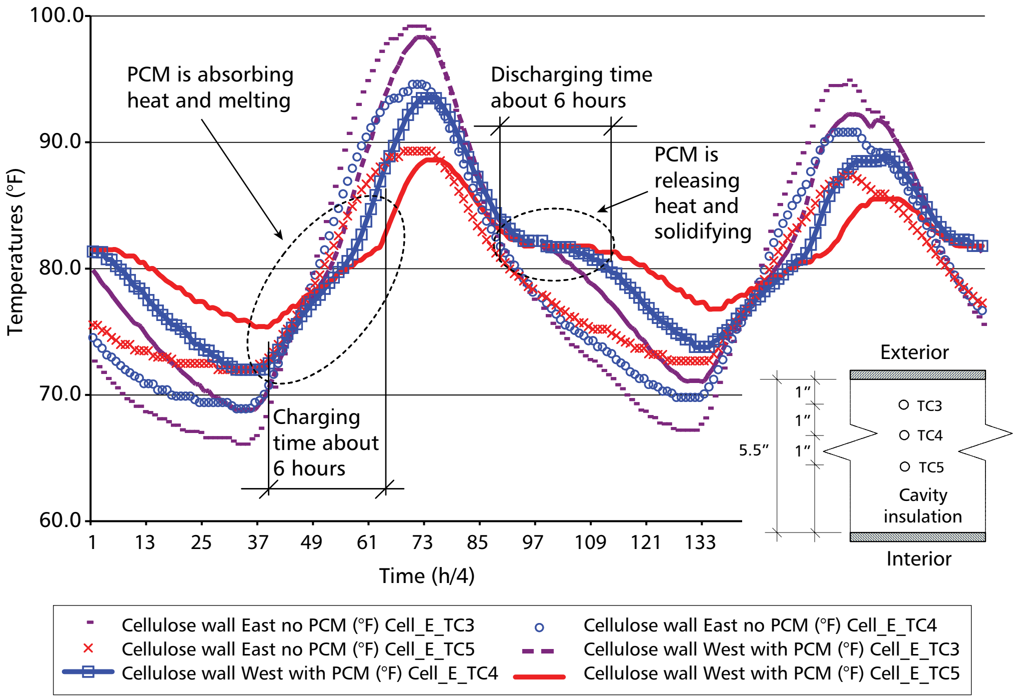


Figure 72 Phase change materials (PCMs) add effective thermal mass; temperature profiles recorded inside wall cavities of south facing test walls with and without PCMs

Source: Kosny et al. (2006)

Minimising solar gains in the tropics is a key strategy, irrespective of the mode in which the building will eventually function (i.e. air conditioned, naturally ventilated or mixed mode). Table 17 shows how solar heat gains may be reduced by the choice of glass.

As was discussed in section 3.4.1, higher levels of insulation in the building fabric can actually have a negative impact on energy consumption. This logic also applies to the specification of glass. In many cases, well specified single glazed facades will be more energy efficient (and more cost effective) than double or triple glazed systems. In addition, it should be said that laminated single glazed panels are sufficient to block disturbing levels of urban noise.

Whereas insulation is only not a key factor, shading is critical. Without shading not only single glazed windows but also double glazing becomes an extremely fragile part of a building's envelope in terms of solar heat gains. Hot humid climates do not experience severe heat ingress through conduction, but due to the tropical location, solar radiation needs to be managed well, hence the solar heat gain coefficient (SHGC) becomes equally important along with the *U*-value. Improved SHGC can be achieved with external shading devices. Various methods of shading are illustrated in Figure 73.

Even in hot humid climates, the need for double glazing has not been satisfactorily proven true. In hotter climates, if the area of glass is significant in the overall area of the building's envelope, double glazed windows and facades could be advantageous. However, double glazing does not replace the need for shading.

As well as direct radiation, diffuse radiation (from overcast skies) can be a significant load in both warm humid and hot humid climates. In this context, large areas of glazing can add significant thermal loads, even when protected from the direct sunlight. In other words, large views of the sky are detrimental to the overall thermal performance of buildings. This is especially true in hot-humid climates. A safe design practice regarding the use of glazing is to adopt the area necessary for good levels of daylight, and not more. Otherwise, occupants in a commercial building may draw their blinds to reduce glare.

Table 17 Representative glass specifications

Glass type (product)	Glass thickness (mm)	Visible transmittance (% daylight)	*U*-value (winter)	Solar heat gain coefficient
Single pane glass (standard clear)	6.35	89	1.09	0.81
Single white laminated with heat rejecting coating	6.35	73	1.06	0.46

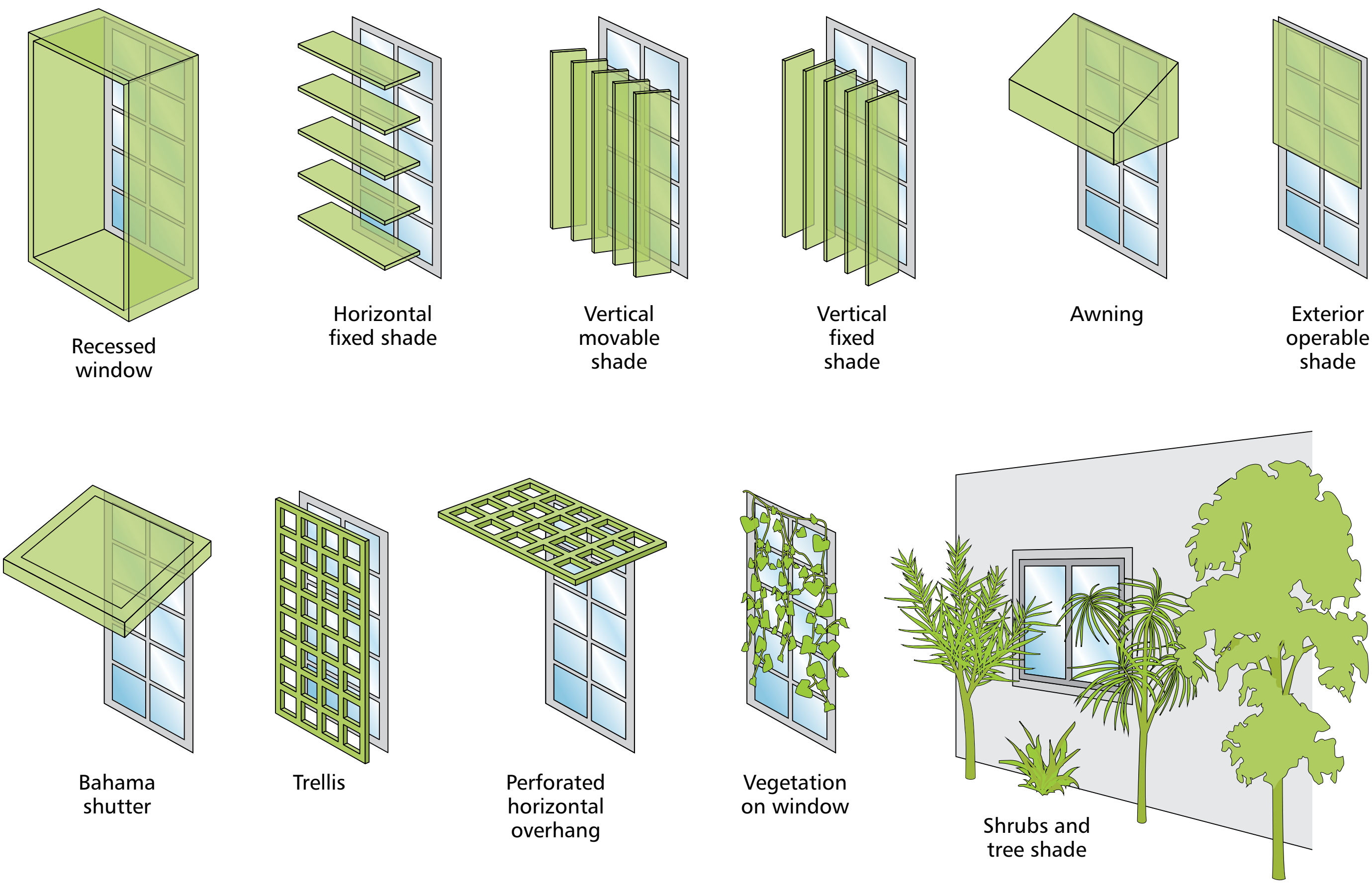


Figure 73 Exterior shading options

Active façades

Conventionally, building façades remain passive and do not change in appearance or characteristics. At most, openable window operation will allow occupants to maintain desired conditions inside the building. Operable overhangs and awnings are used to mitigate negative impact direct solar radiation. They can be operated automatically or manually. However, in urban areas and especially on higher floors, maintenance of these can cause a challenge to building owners. An active façade responds to changing outdoor conditions and helps maintain desired indoor conditions. Some can even anticipate outdoor changes and manage the façade before harsh conditions are experienced. In the tropical context an active façade can be used to manage at least four parameters:

- ventilation
- shading
- glare due to daylight and
- night time cooling.

These strategies are effective for new buildings as well as for existing buildings undergoing retrofit or refurbishment for energy reduction.

Smart facades equipped with automated shading devices, switchable or gasochromic windows, and automated opening/closing operation may help reduce peak loads in many commercial buildings in tropical context. Active façades also can be incorporated with solar thermal collectors installed within glazing systems or building integrated photovoltaic systems

3.4.3 Shading

In locations within the tropical belt, shading is necessary in all orientations given the intensity of solar radiation. This is most crucial for east and west facades given that the sun will rise very quickly in the morning and remains between the 10 am and 2 pm positions for most of the day. The sun sets quickly in the late afternoon in Singapore. Direct solar radiation compromises the thermal performance of buildings. As mentioned in section 3.4.2, in these climatic conditions (warm-humid and hot-humid) both direct and diffuse radiation can add significant thermal loads to internal spaces.

Once all facades are protected from the direct solar radiation (as a minimum), the impact of orientation on the thermal performance of buildings is greatly reduced. However, it may still be relevant to consider the direction of prevailing winds in a natural ventilation strategy.

In tropical climates, shading devices are also a useful means to control excessive levels of daylight (diffuse radiation), which can easily create visual discomfort and high levels of glare. Horizontal shading devices will be more effective than vertical shading in the tropics. They can also serve as a shelter against rain.

On the other hand, oversized shading devices can compromise internal daylight levels. Shading devices can be placed outside, inside or between layers of the facade. Particularly in hot climates external shading devices are preferable and more effective than internal shades or those between layers of the facade, as the short-wave radiation will not reach the interior.

Attention needs to be paid to the design of the shading device to avoid negative impacts on daylight within the building, air flow into the building (in the case of naturally ventilated spaces) and views from the building. Another adverse impact of external shading is the accumulation of warm air between the shading device and the façade which is then admitted into the building if windows are opened to provide natural ventilation. Detaching the shading device from the façades and windows, and avoiding massive shading structures reduce this negative impact on the thermal performance of the space.

The risk of overheating due to the impact of solar radiation in tropical climates imposes restrictions on horizontal openings at roof level. Generally, when used for daylight or ventilation purposes, roof openings should not be horizontal and should be protected with shading devices to avoid the penetration of direct solar radiation. In tropical climates, the additional cooling load from an unprotected horizontal opening in a conditioned space is generally much larger than the energy saved through daylighting, even when high performance glass is used.

3.4.4 Reflection and absorptance

Given the common high intensity of solar radiation, horizontal roofs become a critical point for the overall performance of buildings in the tropics. In this case, the admittance of solar radiation can be effectively blocked in two different ways:

- Reflection, achieved with the use of light colours on the external surface of the roof.
- Shading of the horizontal surface.

In hot humid climates, insulation might be a strategy to be considered. However, its impact has to be accessed over the full 24-hour daily cycle, as insulation will also cut the night time heat rejection, as discussed in section 3.4.1. The use of high thermal mass can also minimise heat gains through the roof.

Among all the design possibilities, the simplicity and high performance of high reflectivity coatings (with low solar absorptance), generally through light colours, should be noted, see Figure 74. Note that metallic roof coverings may have high reflectivity, but usually have low emissivity (also known as thermal absorptance). This restricts their ability to lose heat by radiating it to the atmosphere at night. High performance paints may have solar absorptance as low as 0.16 (reflectivity of 0.84), while retaining emissivity

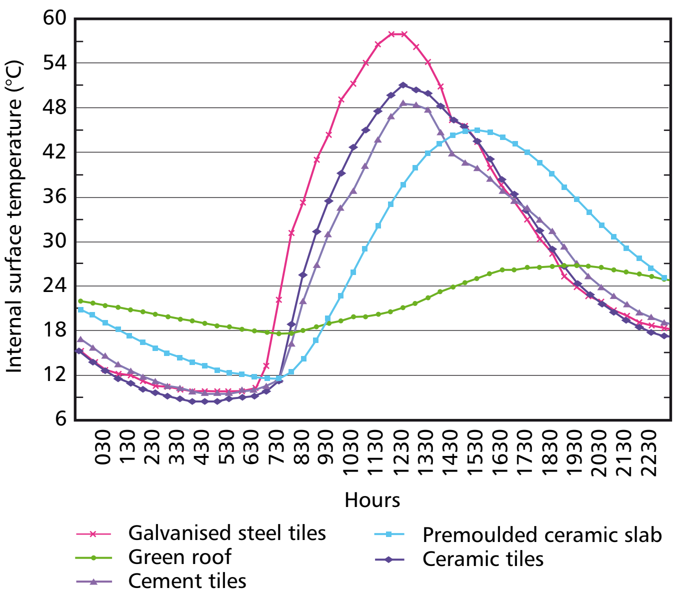


Figure 74 Effect of roof coverings on internal surface temperature

Source: Cardoso and Vecchia (2013)

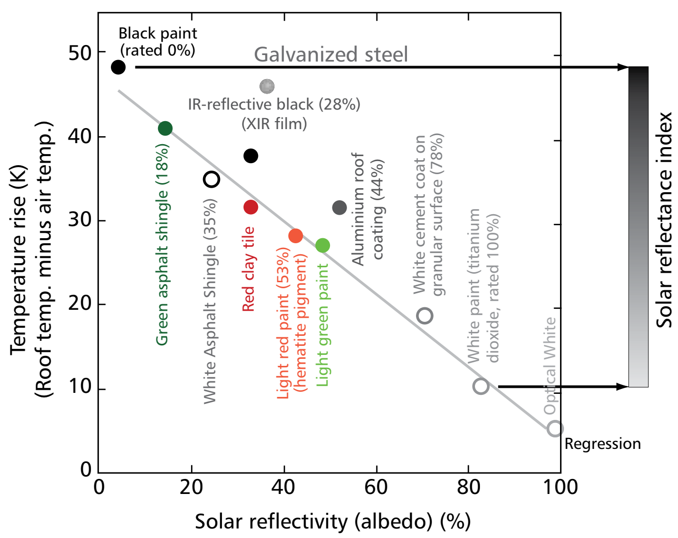


Figure 75 Outdoor measurements on 12 samples of roofing materials

values close to 0.9 (perfect black body radiation), see Figure 75. However, care should be taken to consider the lifetime impact of light coloured roofs. In large cities, pollution and dirt can obscure the colour, while tropical climates may favour the growth of dark-coloured fungal colonies, compromising the performance of the roof. As such, provision must be made for regular cleaning of the roofs (such as provision of a water outlet available on the roof) and periodical repainting.

Green roofs

Another alternative is the use of green roofs, which can have a significant impact on indoor conditions in addition to their wider ecological benefits, see Figure 76. Although they introduce insulation into the roof structure, green roofs are likely to reduce temperatures through evapotranspiration from the vegetation. For more details, the CIBSE *Guidelines for the design and application of green roof systems* (CIBSE, 2013a) should be consulted.

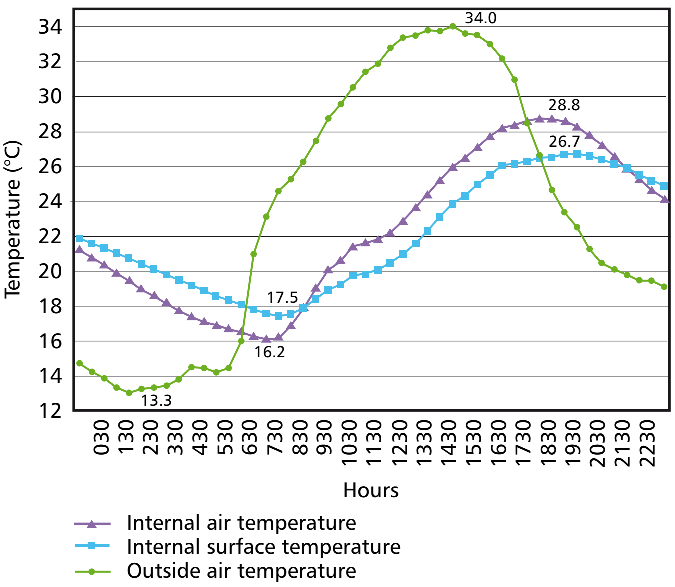


Figure 76 Effect of a green roof on internal surface and air temperatures

Source: Cardoso and Vecchia (2013)

3.5 Hygrothermal behaviour of building materials in tropical climates

3.5.1 Moisture loads in buildings

In warmer climates, and in some air conditioned environments, internal temperatures are likely to drop below the dew-point of the outside air, bringing a risk of condensation on the internal surfaces of functional areas or against the material bounding permeable internal surfaces. Condensation within a building can form as visible surface condensation or can form on surfaces within the building fabric, known as interstitial condensation.

The factors that contribute to condensation in buildings are essentially one or more of the following:

- the presence of excessive moisture levels
- the presence of low temperatures in the building fabric
- uncontrolled flow of water vapour to a region of cold temperature.

The greatest risk of condensation in buildings in tropical climates comes from the ingress of untreated outside air into a cooled space.

Even in unconditioned buildings, high internal moisture loads can sometimes lead to prolonged periods of high humidity or condensation. The main cause of high indoor moisture levels is the generation of warm moist air by domestic activities. The highest levels are produced by:

- cooking
- bathing/showering
- clothes drying
- high occupancy
- high indoor plant concentrations
- uncontrolled moisture ingress.

All of these factors contribute to raising the indoor relative humidity (RH). An increase in RH increases the dew point temperature for the same air temperature. This increases the risk of condensation should the water vapour come into contact with a surface below dew-point.

Tropical climates typically have high outdoor temperatures combined with high relative humidity, resulting in high outdoor vapour pressure. This creates a slight inward vapour flow. For an air conditioned building in a tropical climate the indoor vapour pressure is reduced as both the indoor temperature and humidity are reduced. This results in a large vapour pressure difference, creating a much greater inward vapour flow.

The key principles of moisture management in building cavities is to:

- design to keep moisture out of the building envelope

- allow moisture to escape when it does get in.

Not adhering to the latter principle is the cause of many moisture related building problems.

This section discusses how the failure to consider condensation within the built environment can have serious consequences arising from both surface and interstitial condensation. Some of those consequences include:

- visible and hidden fungus and mould growth
- sick building syndrome leading to serious health problems
- timber decay
- 'phantom' leaks
- saturation of insulation and loss of insulation effectiveness
- corrosion
- loss of structural integrity
- health and safety risk arising from slippery floors.

The longer problems are left unchecked, the more likely they will have structural implications in addition to cosmetic and mould-related problems.

If the building is consistently cooled, e.g. through regular air conditioning, the internal surface of the internal linings may drop below the dew-point of moist external air that may diffuse or leak through the external linings causing condensation. In this case, a vapour barrier creating an airtight layer located toward the outer layers of the wall would be useful. However, if this vapour barrier leaks serious condensation may occur.

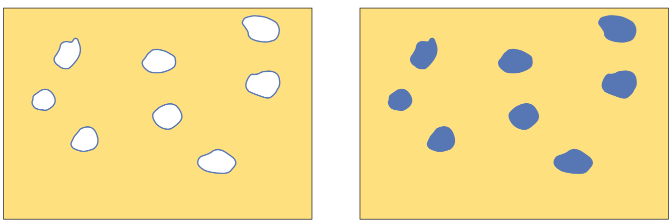
In designing HVAC systems, special care should be taken with dedicated outdoor air systems (DOAS). The outside air should always be treated before being introduced into an air conditioned space, to remove the moisture load and hence avoid condensation.

It should be noted that a common condensation problem occurs when an air conditioned space is adjacent to a naturally ventilated space within a building. In this case the properties of the materials used in the walls become critical.

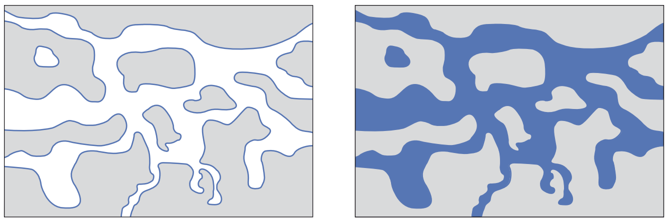
3.5.2 Hygrothermal behaviour of constructions in a tropical climate

In some of the tropical countries in Asia it is common to see walls constructed of clay brick, aerated concrete block, cast in-situ concrete or prefabricated concrete. Wind-driven rain can increase moisture in the wall, which in turn will migrate to indoors. Studies suggest that wind-driven rain can increase moisture content in a wall by 100 times that due to vapour diffusion. Direction, droplet sizes, temperature of water and speed of the rain water on the wall will have a significant impact on migration of moisture. Masonry wall constructions are likely to be affected by rain more than homogeneous wall constructions if not protected with water and vapour barriers. Masonry units such as bricks absorb water; once saturated with water they start releasing it on either side. At this point outdoor temperature, indoor temperature and RH are significant driving factors. Porous mortar made from lime or cement also makes a significant difference.

When rain falls vertically, fewer raindrops hits the surface due to various projections from the wall. Rain coming at an angle hitting a vertical surface has more of an impact. Torrential rain in tropical climates has such characteristics. Raindrops hitting a surface spreads over the surface, which makes a thin water film over the surface. Kinetic energy causes water to start absorbing in to the wall. Capillary action helps water drops to penetrate inside porous material or small cracks, see Figure 77. The warm air of the tropics holds more moisture and helps the wall retain it for a longer period of time. Higher humidity outside drives moisture to penetrate towards the lower humidity inside. In air conditioned buildings, as well as in naturally ventilated buildings, moisture migration through the walls should be avoided by applying water vapour barriers, providing impervious cladding, water resistant paints or even by providing design features such as ledges and overhangs.



Dense materials can store only a limited amount of water before becoming wet



More porous materials can store more water before becoming wet enough to support microbial growth

Figure 77 Hygrothermal behaviour of dense and less dense materials

Source: Morse R and Acker D (2014)

For floors and ceilings in air conditioned buildings the presence of a vapour barrier is important. Where indoor moisture levels are likely to be high, quality airtight construction or the provision of a vapour barrier at the ceiling should limit the entry of indoor water vapour to the roof cavity by also acting as an air barrier.

A damp proof membrane must be installed under slab on ground construction, which protects the building above from moisture.

As a result of previous experience, the Department of Building and Housing New Zealand (DBHNZ, 2006) now advocates the following principles to control external moisture:

- *Deflection*: shed water by a cladding system, including deflecting devices such as eaves and 'weathering' deflectors.
- *Drainage*: a back-up system to direct water that may bypass the cladding back to the outside.
- *Drying*: remove remaining moisture by ventilation or diffusion.
- *Durability*: use materials with appropriate durability within the life expectancy of the building.

Where condensate accumulates in insulation materials, even at levels as low as 1% by volume, it can significantly reduce the thermal resistance of the insulation, as shown in Figure 78. This is because the air gaps in porous insulation are replaced by water, which is a better conductor of heat.

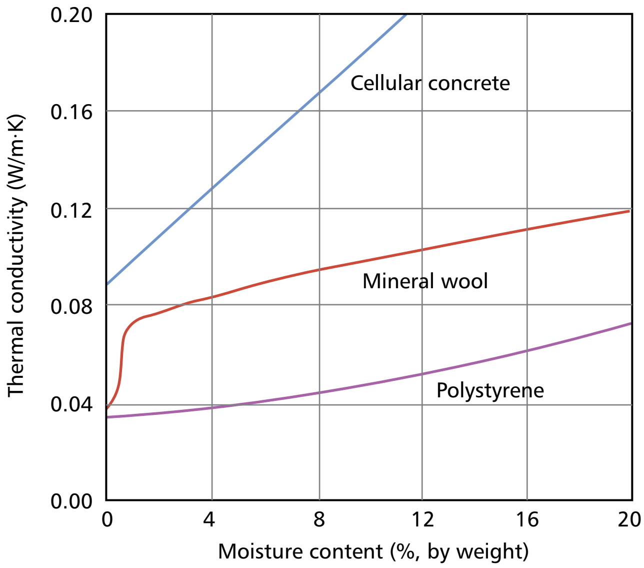


Figure 78 The effect of moisture on the measured thermal conductivity of building materials

The closed cell structure of some foam insulation materials such as extruded polystyrene, phenolic, polyisocyanurate (PIR) and polyurethane (PUR) insulation are less susceptible to moisture and water vapour ingress and so are less prone to loss of insulative performance. Open cell materials, such as mineral wool and expanded polystyrene, are more at risk of loss of thermal resistance. If low emissivity radiant barriers are utilised, even a thin film of condensation will mean the radiant barrier then behaves as if it has a high emissivity coating.