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Flat roof design: thermal insulation

The need to conserve energy in buildings of all types has led to improved standards of insulation, including those of flat roofs in domestic, public and industrial buildings. This Digest discusses the properties required of thermal insulation in flat and low-pitched roofs with continuous waterproof coverings. It reviews the wide range of products available and suggests criteria for selection.

The three principal parts of a flat or low-pitched roof (the deck, the insulation and the waterproof covering) can be positioned to give three practicable and technically acceptable arrangements. Known as the **cold-deck, warm-deck (sandwich)** and **warm-deck (inverted)** designs, they are described in Digest 312, which also offers guidance on roof selection.

Each of these roof designs imposes particular requirements for the thermal insulation and a range of products is available for each type, based upon natural organic materials, synthetic plastics and inorganic materials. There are also a number of composite products which either comprise more than one material of high thermal resistance or which combine the functions of the deck, vapour barrier or waterproof covering as well as providing thermal insulation. Some problems have been experienced with certain composites and care is needed to ensure that they are properly installed and form part of a correctly designed roof system.

This Digest considers the properties required of insulating materials for use with each of the three flat roof design options, and reviews the available types of product in each case. It does not include guidance on roofs with sheet metal coverings which may have particular design requirements related to prevention of corrosion and water entrapment.

The effectiveness of the thermal insulation of a part of the external envelope of a building, such as a flat roof, is expressed as the thermal transmittance or U value. This is the rate of heat transmission through a unit area of the roof for each degree of temperature difference from inside to outside the building.

Fig 1

The current requirements of Building Regulations[1] relating to roofs of buildings are:

Table 1 U-value requirements for roofs

Building type	U-value not to exceed W/(m².K)
Dwelling	0.35
Residential, office, shop assembly building	0.60
Industrial, storage and others	0.70

These maximum values must take into account the heat losses through the aggregate area of any roof lights.

Some older flat roofs were designed using deck materials having some inherent thermal resistance, such as aerated concrete and wood wool slabs. These materials are not normally considered to be insulants since alone they do not permit present requirements for roof insulation to be achieved.

Factors affecting choice of insulation for flat roofs

The choice of a particular form of insulation (loose fill, quilt or rigid board) will be dictated by the roof design — see Digest 312. Table 2 summarises the choice of insulation materials available and the factors that are important in making a choice for a particular design.

Cold-deck

The insulation is placed within the ventilated roof void; rigid boards are often used but quilts and other loose fill materials are equally suitable. These can be used in thicknesses up to 150 mm to meet the insulation requirements in domestic buildings. To avoid risk of condensation, care should be taken to ensure there is sufficient unrestricted air space (minimum of 50 mm depth) between the top of the insulation layer and the deck to allow effective ventilation of the roof void with air from outside the building.

Warm-deck: sandwich

The insulation is placed between the deck and the weatherproof layer and is mechanically fixed or bitumen bonded to the deck or vapour barrier.

Insulating board (softboard) was a common choice before the introduction of rigid foam plastics materials. Its vulnerability to damage by moisture, either by interstitial condensation or by penetration of rain through the roof covering, has led to it being superseded by more suitable materials with a degree of moisture resistance. Table 2 shows the range of acceptable rigid board materials available for insulating the warm-deck sandwich design.

Warm-deck: inverted

This alternative version of the warm-deck design has the insulation above the waterproof covering, protecting it from mechanical damage and temperature extremes. Although the insulation is covered by a suitable ballast, such as stones or paving, it must withstand extremes of temperature and wetting without deterioration of its thermal properties.

In practice, the only materials to satisfy these requirements at reasonable cost, are extruded polystyrene, which has been for some years the most widely specified material for this purpose and, more recently, rigid compressed boards of glass fibre or rock fibre. Cellular glass boards have been proposed for use in inverted flat roofs. However the brittleness of this material and some evidence that freeze-thaw effects cause powdering of the boards in service mean that it cannot be fully recommended.

Extruded polystyrene boards for use on inverted roofs are supplied with various forms of rebated edges, so that the interlocking of the insulation boards reduces the risk of uplift by negative wind pressures or of flotation in heavy rain. This alone is unlikely to be sufficient to prevent displacement of the boards and a ballasting layer of stones or paving slabs is usually necessary — see Digest 295.

A range of composite materials is now available, fabricated from rebated boards of extruded polystyrene with a factory-bonded upper surface of mortar. This is often keyed onto the surface of the plastics board to prevent delamination. With these products ballast (or fixing) may only be necessary around the perimeter of the roof rather than over the total roof area. At present there is little experience of the performance of these products in service.

Caution is given against the practice of bonding the insulation to the membrane to overcome wind uplift; little is known about the ability of the membrane to withstand imposed movements caused by thermal movement of the insulation.

Performance requirements for flat roof insulation

The prime requirement of a thermal insulation material is that it should resist the passage of heat. This depends principally on two factors:

- **its thermal resistivity**
- **its thickness**

These factors are used to calculate the thermal resistance (*R*) of a material.

In addition the insulation should have:

- **dimensional stability** under conditions of installation and the likely conditions of service (eg variations of temperature and exposure to moisture)

- **mechanical properties** which will allow the material to withstand stresses imposed in service and in handling during construction or installation

- **durability** to enable it to sustain performance throughout service life

- **very low moisture absorption** (inverted roof design) to preserve thermal resistivity.

- Sufficiently **low resistance to water vapour transmission** (cold-deck design and, in some cases, warm-deck sandwich design).

Thermal resistance

The thermal resistance of a roof (R_r) is the sum of the thermal resistance values of the individual layers which comprise the roof, the largest value usually being that of the insulation, plus inside and outside surfaces resistances (see Digest 108).

$$R_r = (R_1 + R_2 + R_3 \ldots..) + (R_{si} + R_{so})$$

The thermal resistance of each layer (assumed to be homogeneous) is a simple multiple:

Thermal resistance of roof layer =
thickness × thermal resistance of material

Thermal resistivity is conventionally expressed in the following units:

(m. K)/W

and thermal resistance is expressed in units of:

(m².K)/W

The thermal transmittance for the whole roof structure (the 'U-value') is the reciprocal of its total thermal resistance:

$$U = \frac{1}{R_r} = \frac{1}{(R_1 + R_2 + R_3 + \ldots) + (R_{si} + R_{so})}$$

Data for the thermal resistance of insulation materials are generally presented either as the thermal conductivity of the material (as a function of temperature) or as the thermal resistance for a specified thickness of the material as shown in Fig 2 and Table 3 (rigid boards) and Fig 3 (quilt and loose fill insulation).

By knowing the thermal resistance of other materials in the roof the required thickness of insulation to achieve a specified maximum U-value can be estimated. Such calculations assume steady state conditions in the roof and although this may not be truly representative of what happens in service they will usually give a suitably accurate estimate of insulation thickness required. In practice, variable exposure conditions in service may influence the rate at which heat moves through the roof, in particular:

- The variation of temperature with time, both within and outside the building

- Variation in ventilation rate (cold deck roofs)

- The influence of radiation mainly to and from the external roof surface.

- Thermal inertia of the roof.

At present in the UK there are no recognised procedures for taking account of these influences during design: when one or more is judged to be likely to have a significant effect on heat flow it is recommended that, as a precaution, insulation thickness is increased by 5 to 10% above that estimated by the standard U-value calculation above.

The thermal resistance of some insulation board materials changes with time. This happens with rigid foam plastics which contain a gas of low thermal conductivity (eg fluorinated hydrocarbons) within the closed cells. Foamed polyurethane boards age in this way, as a result of the diffusion of the gas through the cell walls and its replacement by air. The effect is reduced when the surfaces of the boards are laminated with relatively impervious materials such as aluminium foil or glass reinforced polyethylene. Under these circumstances it is likely that the thermal conductivity of foamed polyurethane will increase only slightly: an increase of about 5% over ten years has been measured in the laboratory[2], while for uncovered boards the thermal conductivity increased by nearly 30%. Phenolic insulation boards also contain fluorinated hydrocarbons and although the cells of these boards are smaller and less permeable an ageing effect cannot be discounted. Ageing effects should be borne in mind when comparing the thermal resistance data given in Fig 2 and, in practice, design values should be conservative when considering the use of materials containing gases of low thermal conductivity.

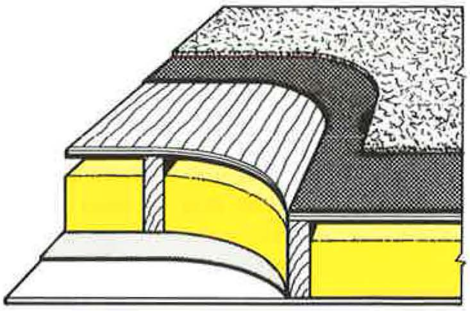
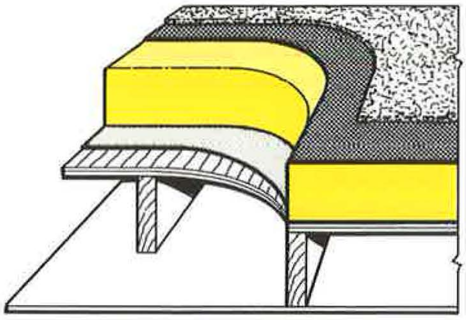
Dimensional stability

Dimensional stability is of major importance only with rigid board materials used in **warm-deck sandwich roofs,** where the insulation is usually fixed to the overlaying waterproof membrane and/or the deck below.

Temperature and moisture content variation can cause dimensional changes. Where both effects are encountered simultaneously, they tend to have opposing effects, since increases in temperature will tend to increase the rate of moisture loss from the material; this causes shrinkage. Typical values of linear dimensional change with temperature can be calculated from the coefficients given in Table 3.

The thermal movement of foam plastics insulation became the subject of much discussion and investigation following numerous premature failures of bituminous roofing membranes fully-bonded to the

Table 2 Choosing insulation for flat roofs

	Cold-deck	Warm-deck (sandwich)
		
Factors affecting choice	Insulation partially fills the roof void and because it is protected from the weather and has no supportive role, loose fill types can be used. Rigid insulation can be cut to size for laying within the cavities in the roof void.	Rigid insulation is needed to support the waterproof membrane and roof traffic. The insulation is close to the roof surface and will experience large fluctuations in temperature. To prevent thermal movement and risk of damage to the membrane the roof should either incorporate insulation with a low coefficient of thermal expansion or an overlay between the insulation and the membrane. Insulation must be compatible with the bonding materials used.
Broad category of insulation used	Most materials suitable	Rigid insulation boards
Suitable types of insulation		
Natural organic materials	Cellulose fibre	Bitumen impregnated insulating board* (usually used as an overlay) Wood wool cement* Corkboard*
Synthetic foam plastics	Loose fill or boards	Expanded polystyrene (beadboard) Polyurethane Polyisocyanurate Phenolic
Synthetic foam (foamed in-situ)	Not appropriate	Not appropriate
Inorganic	Glass fibre quilt Rock fibre quilt	Cellular glass Glass fibre (high density) Rock fibre (high density) Perlite
Others/composites	Not appropriate	Cork/polyurethane Fibre building board/expanded polystyrene Perlite/polyurethane Perlite/expanded polystyrene

*These have insulating properties but may have insufficient thermal resistance to be used as the sole insulating material

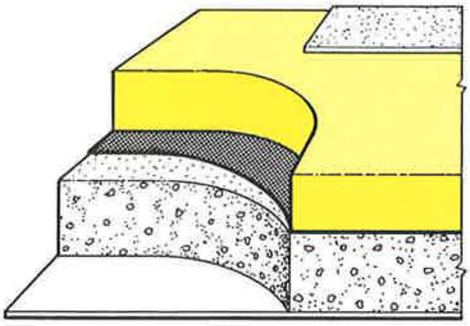
Warm-deck (inverted)	Thermal upgrading existing roofs
	
Rigid insulation is needed to support ballasting and roof traffic. Although covered by a layer of stones or slabs, the insulation is not protected from exposure to extremes of temperature, or from rain/melting snow which can percolate through joins in the insulation. Insulation must not absorb moisture and must be resistant to freeze/thaw cycles without deterioration in thermal performance.	Various factors apply, depending on modification and existing roof design
Rigid closed-cell insulation boards. Some composite boards are now being marketed with mortar bonded to the upper surface to act as ballast.	Various
Not suitable Extruded polystyrene	Insulation selection depends on modification and existing roof design (see text)
Not appropriate	Polyurethane Polyisocyanurate
Glass fibre (compressed) Rock fibre Extruded polystyrene/mortar Extruded polystyrene/grp	Insulation depends on modification and existing roof design

Table 3 Properties of rigid board materials

	Density *kg/m³*	Typical thermal resistivity *(m.K)/W*	Coefficient of linear expansion *(per °C × 10⁻⁵)*	Moisture vapour resistivity *MN.s/g.m*
Foamed plastics				
Expanded polystyrene	16 – 40	30	5 – 7	100 – 600
Extruded polystyrene	28 – 45	40	7	600 – 1300
Polyurethane	32	45	2.7	500 – 1000
Polyisocyanurate	32	45	2.5 – 3.5	1000
Phenolic	35 – 60	50	3-5	200 – 750
Natural organic materials				
Fibre building boards:				
Insulating board	210 – 300	15	negligible	15 – 60
Bitumen impregnated insulating board	240 – 330	19	negligible	450 – 750
Corkboard	120	24	negligible	50 – 200
Inorganic materials				
Perlite	175	20	0.7	28
Rock fibre	200	30	negligible	15
Glass fibre	125	25	negligible	7
Cellular glass	125	16	0.85	10,000

insulation in warm-deck sandwich roofs. Failures typically occurred as splits in the membrane over the gaps between the insulation boards. Detailed investigation was made of the observed movements at such gaps in flat roofs incorporating various foam plastics insulation with different forms of connection between the insulation and the membrane. These were supplemented with tests on laboratory models of warm-deck constructions[3][4].

The results of this research identify the key factors which influence the amounts of thermal movement which can occur in flat roofs of sandwich construction. A number of variations on this design option are available which minimise the stresses in the membrane (and thus effectively reduce flexural fatigue):

- **Choice of insulant** The maximum thermal movements at joints between extruded polystyrene boards are generally about twice as large as those observed with other rigid foam plastics boards. This insulant is not therefore now recommended for use in warm-deck sandwich roofs. Expanded polystyrene (beadboard) on the other hand has been used successfully with this type of roof, although here it is recommended that an overlay (13mm bitumen-impregnated insulating board or perlite) is positioned between the insulation and the fully-bonded membrane.

- **Fixing insulation to deck** By bitumen-bonding the insulation to the deck the maximum thermal movements at joints in the insulation can be reduced to about 50% of those observed in roofs of similar design but with mechanical fixing of the insulant to the deck.

- **Bonding of membrane to insulation** By using a perforated first layer for the built-up bitumen felt membrane, a partial bond is created between the insulant and the membrane. This results in greatly reduced local stresses in the membrane with given amounts of thermal movement at gaps in the insulation. The reduction in fatigue stressing can give a very marked increase in the potential life in service of a built-up membrane.

Other dimensional changes, clearly independent of temperature and moisture movement, have been observed in rigid foam plastics boards stored under steady conditions for as long as two years after manufacture. The two major products investigated showed opposite effects: extruded polystyrene boards tended to shrink, while polyurethane grew slightly in linear dimensions (in both cases only fractionally). Similar effects were observed in the measured movements on roofs in service when corrections for thermal effects were made. Visual observations on a two year old roof with polyurethane insulation revealed that many gaps between the boards had closed up so that adjacent boards were closely butted together. In roofs with polystyrene insulation, the opposite effect can impose additional tensile stress on fully-bonded membranes over gaps in the insulation layer.

Other materials which may be considered for use in warm-deck constructions have significantly lower thermal movements than the rigid foam plastics. Cellular glass may be considered virtually stable to temperature change: corkboard, perlite and compressed glass fibre or rock fibre all exhibit only very slight thermal movement (see Table 3).

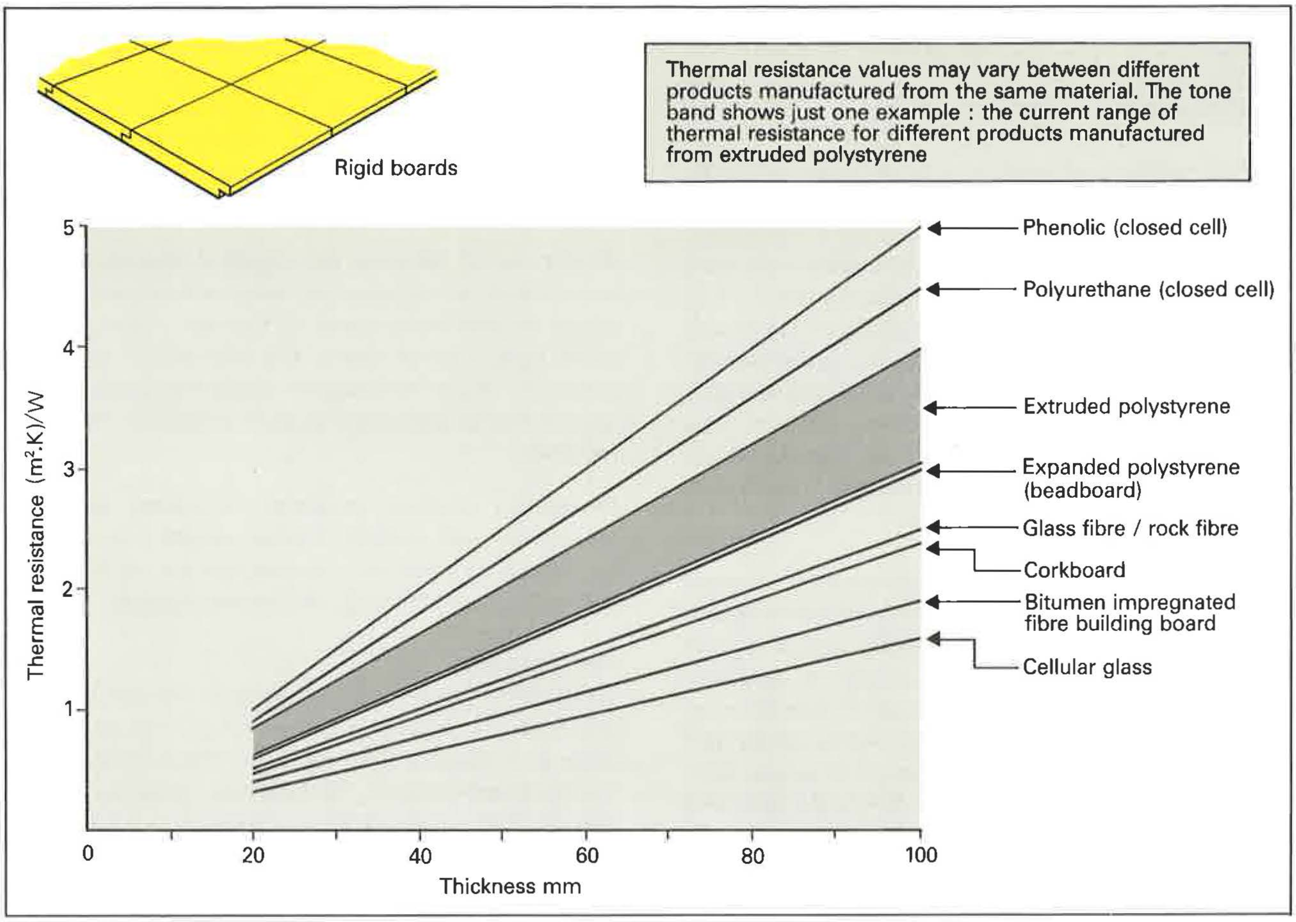


Fig 2 Typical resistance values for a range of materials and thickness: rigid boards

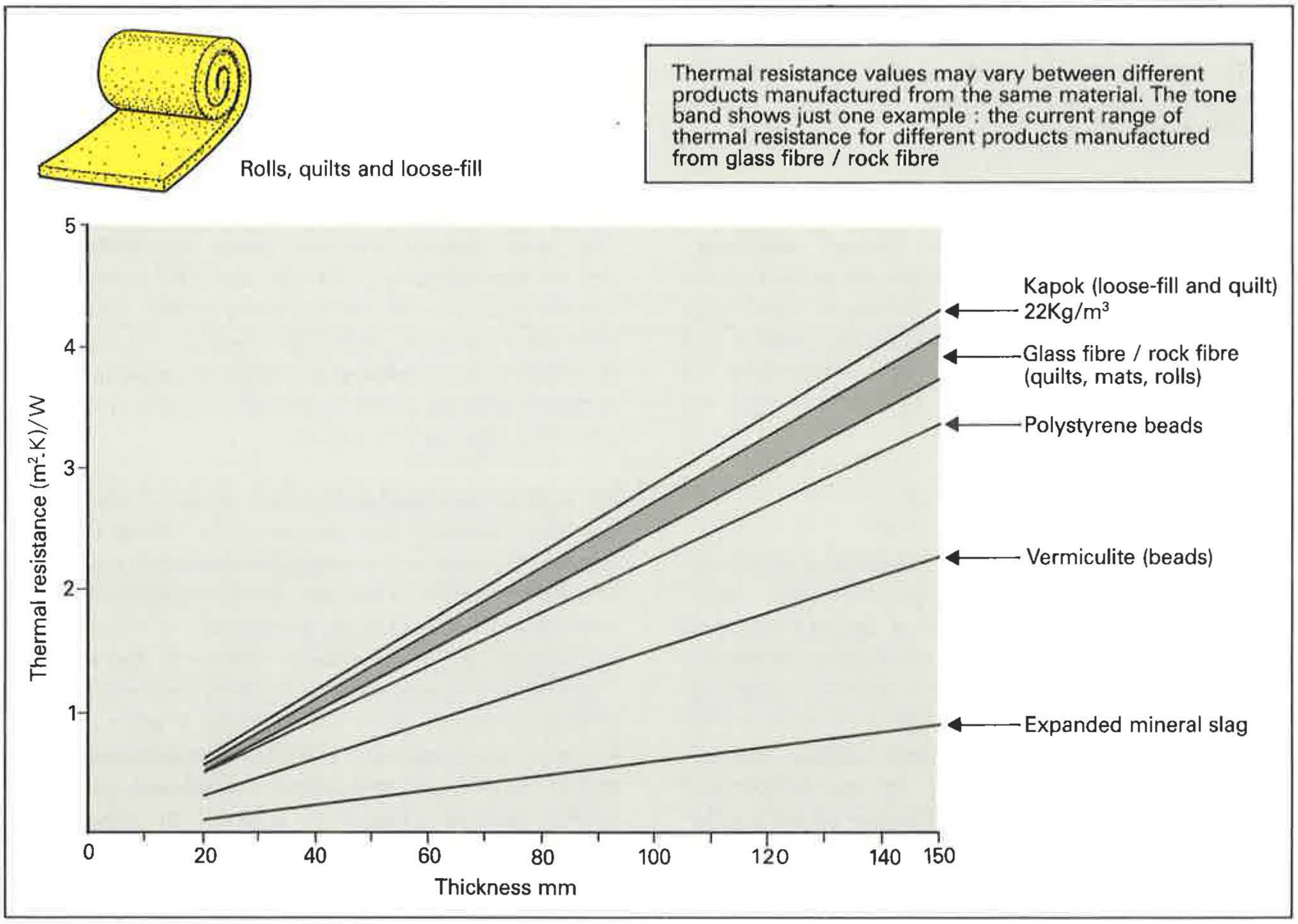


Fig 3 Typical resistance values for a range of materials and thickness: rolls, quilts and loose fills

Resistance to moisture
Insulation is likely to become exposed to moisture in vapour, liquid or solid forms at some stage during installation, storage on site or in service.

The **inverted flat roof** is designed to allow such exposure in service. This necessitates the use of a closed-cell material which absorbs only a small proportion of water, and does not suffer significant loss of thermal resistance under these conditions. In addition the insulation must not be degraded by the repeated freeze/thaw temperature cycles which may occur in inverted roofs in northern latitudes in winter. Extruded polystyrene meets these requirements and is widely used in the construction of inverted flat roofs. Although not widely used, rigid boards of heavy duty compressed glass fibre or rock fibre are also suitable for use.

Flat roofs of the **warm-deck sandwich** type are designed to minimise the risk of interstitial condensation which could damage and impair the effectiveness of the insulation: an effective vapour barrier is generally provided immediately below the layer of insulation. In roofs of this type the performance of the whole roof structure in relation to the transmission of vapour from within the building through the roof is important, and should be carefully assessed by the designer from a knowledge of the vapour diffusion resistance values of the various layers which comprise the roof.

Vapour diffusion resistivities are given in Table 3; they are the reciprocals of vapour diffusion permeability, ie the rate of mass transfer of water vapour through unit area of the material, as a ratio of the vapour pressure difference across unit thickness. The units of vapour diffusion resistivity are:

MN.s/g.m

Analogous with calculations on thermal resistance, vapour diffusion resistance of a particular layer of a roof (V_1) is calculated by multiplying thickness and resistivity of the material. The vapour diffusion resistances of the layers of a flat roof may be summed arithmetically to calculate the total resistance (V_r) of the roof to transmission of water vapour:

$$V_r = V_l + V_2 + V_3 + \ldots.$$

Knowing the distribution of vapour resistance across the layers of the roof enables the rates of accumulation of condensed water to be calculated at discrete locations within the roof. This is done for specified psychrometric conditions within and outside the building, assuming steady-state conditions throughout a winter (for example, 60 days is often assumed). Similarly, the rate of evaporation and dispersion of the condensed moisture during the succeeding summer period can be calculated.

The failure to ensure correct design of warm-deck flat roofs has led to frequent damage to organic-based materials such as strawboard and insulating board which are found to degrade after prolonged exposure to condensed water. This is not a serious problem with foam plastics and mineral-based materials. Nevertheless, interstitial condensation can cause serious inconvenience and damage and is often mistaken for leakage of rain through the waterproof covering.

Absorption of moisture can cause a loss of thermal resistance in some materials, and a progressive decline in the thermal performance of the roof. Table 4 gives some data[5] which shows the amounts of absorbed water (by volume and weight) which will cause a 40% loss of thermal resistance for some vulnerable insulation materials.

Closed-cell foamed products, including extruded polystyrene and phenolic boards, absorb only a small percentage by weight of moisture, and are not therefore subject to loss of thermal resistance in this way.

Fire properties
Insulants may be either combustible or non-combustible and their functional requirement of limiting heat flow tends to increase problems in a fire. The contribution to fire development from foam plastics insulants, widely used in roof constructions, is likely to include active emission of heat, smoke and decomposition products. The risk to life from roof fires is, however, low as evidenced by advice on control under Building Regulations being restricted to prevention of the spread from neighbouring properties (BS 476:Part 3:1958). Extensive involvement of the roof has in the past caused serious financial loss (both direct and indirect) particularly in industrial premises where a self-supporting fire has spread unconfined beyond the reach of fire-fighting equipment; the introduction of flammable insulants increases this risk and requires care in the design and installation of systems incorporating them. The foam plastics insulants most commonly used include thermoplastic products, such as expanded or extruded polystyrene, which, when heated, soften and melt before ignition, and thermosetting products, such as phenolic, polyurethane and polyisocyanurate, which undergo localised charring, followed by active flaming when the volatiles mix with air.

For a **warm-deck sandwich** design, spread of flame over the roof covering and subsequently penetration to involve the underlying insulant will determine the extent of fire involvement of the roof. Break-through of fire into the building will be largely determined by the material and design of the roof deck which, in this type of construction, should be able to resist penetration until after the external fire is extinguished. Interaction may however occur between individual components of the system eg bitumen and molten polystyrene may flow readily through troughs in a steel roof deck and penetrate joints or gaps to fall, possibly still burning, into the building below.

Spread of flame over the surface of the roof covering depends largely on the ability of the surface to resist ignition and penetration by fire on exposure to flames from an adjacent fire. The deflection of flames by wind increases the risk of ignition and emission of volatiles once the insulant is exposed; where the rate of heat release from the insulant is high a risk of unconfined spread of fire over the roof can occur. The fire exposure test specified in BS 476:Part 3:1958 does not simulate this situation, only a minimal radiation severity being specified for the test, typical of that likely to be experienced when the roof is exposed to fire from a neighbouring building.

The **warm-deck inverted** roof, in which the insulant is generally covered by a ballasting layer of stones or by paving slabs will be less vulnerable to the risk of external fire sources to unconfined fire spread, the high thermal capacity of the ballast preventing involvement of the insulant below.

In the **cold-deck** roof, loose laid insulation in the form of mats or quilts or granular infill between the joists within the loft area can increase the risk of ignition by preventing dissipation of heat. If a combustible insulant is brought into contact with a heat source, particularly where this is buried by the insulant as may occur with defective electrical insulation or an overheated flue pipe, smouldering may be initiated. This may spread slowly throughout the area and finally involve flammable contents or combustible roof construction.

In assessing the possible contribution of roof insulation materials to fire within a building, the composition and construction of composite products may be important. Laminations on the surface of board materials exposed to fire from below will be important in influencing the extent and rate of spread of fire by controlling the release of heat from the insulant into the layer of hot flowing gases below the insulated deck.

Addition of flame retardants to the insulants is of less importance than ensuring that their direct exposure to air is delayed as long as possible; in the case of some thermosetting products the formation of a rigid char layer on the exposed surface provides an effective protective layer but the initial contribution to flame spread may be high unless a suitable flame retardant finish is applied.

Table 4

	Moisture content required to reduce thermal resistance to 60% 'dry' value	
Material	**% by weight**	**% by volume**
Insulating board (softboard; wood-based)	75	21
Perlite board	85	13
Expanded polystyrene (beadboard)	1600	23
Glass fibre board	60	13

Emission of smoke from the burning insulants may be heavy (Table 5) but this is true also of some additional roofing finishes such as bitumen. The comparative density of smoke emitted from polymeric insulants depends more on the extent of their involvement in the fire and on the extent of subsequent dilution with air than on their inherent smoke emission characteristics under given combustion conditions.

Similarly, the decomposition products generated on combustion of individual insulants can vary widely depending on external conditions such as the intensity of heating and the presence or exclusion of air from the combustion zone. In general, all organic materials generate carbon monoxide in quantities largely determined by the fire environment; additionally, other toxic or noxious combustion products may be formed but usually in quantities such that a lower risk to life is involved although individual products may be more inherently dangerous.

In the case of fires above the roof deck, few problems are caused by smoke and toxic decomposition products and the risk to life is usually restricted to members of the fire brigade who are supplied with appropriate safety equipment. Where the insulation is installed below the roof deck however, a layer of hot smoky gases may be generated. In buildings with large undivided areas, the design must provide venting to restrict fire spread and contamination of the building below. Depending on building use and design, this contamination can introduce a risk to life (Digest 260).

Strength properties

Rigid board materials need to be sufficiently robust to withstand stresses imposed by handling during installation and by the conditions of service. Boards which are brittle or friable are particularly vulnerable to damage during storage and handling on site, and liable to high rejection rates because of damage to edges and corners of boards.

Compressive strength must be adequate to withstand any imposed loads without damage or permanent deformation. When loads are limited to normal pedestrian access for maintenance, a minimum compressive strength of 175 kPa is recommended. Where roofs are expected to carry higher loads (eg heavy maintenance equipment) higher compression strength will be required or consideration given to providing independent walkways or surface structures.

If the insulation is not continuously supported, as in roofs with troughed metal decks, boards must have sufficient bending strength to carry the imposed service loads over the trough openings. Guidance is available on board thicknesses required to bridge trough widths of 75 mm and above[6]. In practice bending strength may

Table 5 Fire properties of insulation materials

Insulation types	Combustibility	Ignitability	Major decomposition products	Melting characteristics
Synthetic foam plastics (rigid materials)			CO is emitted from all organic products	
Polystyrene	Combustible	Small flame[1]	Heavy smoke — some styrene	Melts
Polyurethane	Combustible	Small flame[1]	Heavy smoke — some nitrogenous species	Chars
Polyisocyanurate	Combustible	With high additional radiation	Heavy smoke — some nitrogenous species	Chars
Phenolic	Combustible	With additional radiation	Little smoke — some phenol formaldehyde	Chars
PVC	Combustible	With high additional radiation	Heavy smoke — some HCl	Melts
Natural organic materials				
Insulating board (softboard; wood-based)	Combustible	Small flame	Smoke — some acrolein[2]	Smoulders and burns
Wood wool cement	Combustible	Decomposes without flame	Very little decomposition	Very slow decomposition
Corkboard	Combustible	Small flame	Smoke — some acrolein	Smoulders and burns
Inorganic materials				
Cellular glass	Non-combustible	Nil	Nil	MP 500 – 800 °C
Rock fibre	Non-combustible[3]	Limited[3] flaming	Negligible	MP 800 – 900 °C
Glass fibre	Non-combustible[3]	Limited[3] flaming	Negligible	MP 500 – 600 °C
Perlite	Non-combustible	Nil	Nil	>1200°C
Loose fill, quilts etc				
Polystyrene beads	Combustible	Small flame	As polystyrene	Melts
Vermiculite	Non-combustible	Nil	Nil	>1200°C
Cellulose fibre	Combustible	Smoulders[4]	Light smoke — some acrolein	Smoulders and burns

Notes

1 Performance depends on a flame retardent treatment
2 Depends on ventilation
3 The traditional BS test permits a very limited flame emission
4 Initiation of smouldering may result in subsequent flaming

Surface spread of flame (BS 476:Part 7:1971)	Rate of heat emission
Not testable	High
Class 3/4	High
Class 1	High on exposure to high intensity
Class 1/2	Low
Class 1/2	Low
Class 4	Low after initial peak
Class 1	Minimal
Class 4	Primarily smouldering
Class 1	Nil
Class 1	Virtually nil
Class 1	Virtually nil
Class 1	Nil
Not testable	High
Not testable	Nil
Not testable	Primarily smouldering

dictate the minimum thickness of insulation to be used, regardless of the thermal requirement for the roof, since the effective resistance to these bending stresses will increase as the square of the board thickness. The presence of a vapour barrier immediately below the insulation will provide additional resistance to bending.

In a warm-deck roof, without mechanical fixings, wind suction and gusting can produce extreme local loading on the insulation and on the bonding between the insulation and its facings, and to the deck and membrane, respectively. The stresses imposed by these extremes of wind suction are especially onerous for partially-bonded membrane systems, in which the area of adhesion between the membrane and the top surface of the insulation may be (at very minimum) 10% of the total roof area. Although there are test methods for assessing the laminar strength of insulation board materials there are as yet no agreed performance levels for this property. There are also test methods available which can be used to evaluate the laminar strength of complete or partial roof systems under simulated natural wind exposure and negative pressure[7],[8].

Impact resistance is a less important requirement for insulation boards, though the more brittle materials, such as cellular glass, may prove vulnerable.

Rigidity, strength and dimensional stability of foamed plastics materials may be greatly increased by the incorporation of a reinforcing matrix, such as glass fibres; polyurethane boards of this type are available.

Thermal upgrading of existing flat roofs

Many flat roofs were constructed at a time when general standards of thermal insulation of buildings were lower than present regulations require. In view of the high costs incurred by heat losses from buildings, it may be economic to add insulation to these roofs. This is preferably done when remedial work is to be carried out to replace roof coverings.

The upgrading of flat roofs may preserve the original type of construction, merely increasing the thickness of insulation. In other cases it may be preferable to modify the roof design. For example, a cold-deck roof can be converted to a warm-deck (sandwich) construction; or additional insulation could be placed above the present weatherproof covering to produce an inverted roof. The choice of modification will depend in part on other improvements, besides thermal performance, which may be considered necessary. For example, whether the use of tapered insulation would be of benefit in improving falls. The condition of the existing waterproof membrane may also govern the type of modification that is possible.

In most cases, the criteria for selecting an insulation material for upgrading work will be similar to those when designing a new roof, although options may be limited by the roof perimeter upstand height.

Foamed in-situ polyurethane has been used in thermal upgrading. It has the advantage that it can be applied over the existing roof covering of a warm-deck type of roof, however it is recommended that the existing membrane is checked to be fully waterproof before application. The foamed polyurethane is applied by special spraying equipment, usually in a series of passes across the roof, alternately at right angles and to a total depth of at least 50 mm. A protective coating must be applied, either an elastomeric polyurethane layer or cold-applied bitumen with chippings, to prevent degradation of the polyurethane foam by solar radiation and its gradual erosion by rain. Difficulties in applying this product to flat roofs in the British climate have limited its use. The surface to which the foam is to be applied must be completely dry to obtain adequate adhesion. it is also difficult to spray in windy conditions because the foam can be blown on to adjoining property.

When placing additional insulation above the existing weatherproof membrane, whether to form an inverted roof or to convert a cold deck into a warm-deck construction it is important to ensure that there is no risk of condensation below the membrane, particularly if high humidities are likely in the room below the roof. Calculations should be carried out to check that the added insulation does not result in dewpoint below the waterproof membrane. As a general guide, at least 50% of the total thermal resistance of the modified roof should be on the upper (outer) side of the membrane.

With **cold-deck** roofs care must be taken to ensure that added insulation does not block ventilation openings or restrict ventilation flow within the roof cavity.

Environment and safety considerations

It should be noted that current concern over the environmental effects of fluorinated hydrocarbons may result in future restrictions on the use of materials containing these compounds.

Those working with mineral wool (rock, slag or glass) should follow health and safety recommendations supplied by manufacturers or seek advice from the Health and Safety Executive[9].

References and further reading

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BS 6229 : 1982 Code of practice for flat roofs with continuously supported coverings

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