MINISTRY OF FEDERAL AFFAIRS & GENERAL ADMINISTRATION

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BUILDING ENERGY EFFICIENCY IN NEPAL

Manual on

APPLICATION OF BUILDING INSULATION MATERIALS

universität innsbruck
Unit of Energy Efficient Buildings

MinErgy

Greentech Knowledge Solutions Pvt. Ltd.

UNE Normalización Española

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Preface

Building materials play a major role in achieving thermal comfort and high energy efficiency in buildings. An informed selection of building materials can optimize the indoor temperature by 2 to 5 degrees Celsius and reduce energy consumption by up to 40 per cent. The building envelope is particularly crucial in controlling heat gains or losses inside a building, as well as in protecting its occupants from harsh external weather conditions.

Building insulation controls heat gains or losses through walls and roofs. It is particularly beneficial in cold climates, making it especially relevant for Nepal. However, the market for energy-efficient building materials, such as insulation, high SRI paints, walling materials, dynamic shading and high-performance glass, is still in a nascent stage in Nepal.

This manual provides an overview of building insulation materials, their thermal characteristics and how these affect the energy consumption and comfort levels in buildings. It also explores different types of insulation materials and the various compositions in which they can be applied to roof and walls. Additionally, it describes construction guidelines for these combinations.

Proper installation of insulation materials is essential to ensure maximum benefits to the building.

The manual is designed for both building designers, who select appropriate insulation for their projects, and construction workers, who are involved in the application of insulation material in buildings.

This manual has been developed under the project "Building Energy Efficiency in Nepal" (BEEN), supported by the SWITCH-Asia Grants of the European Union.

The authors seek ideas and case studies from the building construction industry in Nepal on building insulation.

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Our Ref. No.:

Message

In recent years, the need to rethink the approach to the building design and use of materials has gained significant momentum in Nepal. This shift is reflected in the Sixteenth Plan, which endorses a policy prioritizing investments in energy efficiency and climate adaptation, including for residential buildings. Furthermore, underscoring the importance of energy efficiency, Annual Budget 2081/82 explicitly calls for giving priority to climate responsiveness and adaptation in all physical infrastructure constructions. Therefore, the federal, provincial and local level governments will prioritize climate adaptation and energy efficiency in their building constructions. These policies will contribute to Nepal achieving the Nationally Determined Contributions (NDC) targets of net-zero greenhouse gas (GHG) emissions by 2045.

Nepal's unique geographical terrain, along with its varied bioclimatic zones, presents significant challenges to achieving thermal comfort in buildings, especially in extreme climatic zones. Traditional knowledge and practices, which often inherently incorporated effective thermal insulation in building design and construction, are gradually vanishing, whereas modern practices often lack such considerations, resulting in high energy demand for space conditioning.

The BUILDING Energy Efficiency in Nepal (BEEN) project, funded by the European Union under the SWITCH-Asia Grants Programme, is being implemented in partnership with the Ministry of Federal Affairs and General Administration (MoFAGA) to support local and federal governments, as well as the private sector, in reducing carbon emissions in the building sector. The *Manual on the Application of Building Insulation Materials*, is a timely and crucial resource aimed at enhancing energy efficiency in buildings across Nepal. It provides comprehensive guidelines on the selection, placement and application of various insulation materials, emphasizing their importance in creating energy-efficient and climatically responsive buildings.

We believe this manual will serve as an invaluable tool for architects, builders, engineers and all actors involved in the building design and construction industry. By adopting the best practices outlined in this manual, we can collectively work towards reducing energy consumption, lowering carbon emissions and promoting sustainable development in Nepal.

We extend our sincere thanks to all contributors and partners who made the development of this manual possible. Together, let us build a more energy-efficient and sustainable future for our nation.

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Kali Prasad Parajuli
Joint Secretary
20 September 2024

EUROPEAN UNION

DELEGATION TO NEPAL

Head of Cooperation

Message

The building sector is one of the key sectors with significant energy consumption and emissions in the world. In the European Union, buildings are the primary energy consumer, contributing to 40% of total energy consumption and 36% of Greenhouse Gas (GHG) emissions. This data sets the urgency for providing sustainable and energy-efficient solutions in the building sector in order to reduce environmental problems and mitigate climate change impact.

Given the critical role of the building sector in minimising resource and energy consumption, thereby reducing the carbon footprints, the European Union has devised various policies to achieve its energy and climate goals. These policies aim to minimise energy consumption, improve thermal comfort of existing buildings and promote smart solutions and the use of resource-efficient materials in the construction of new buildings. In particular, the EU's legislative framework, which includes the revised Energy Performance of Buildings Directive and the revised Energy Efficiency Directive, sets ambitious targets for new and renovated buildings. These targets aim to reduce GHG emissions by at least 60% in the building sector by 2030 and achieve a decarbonised, zero-emission building stock by 2050. These directives for energy-efficient buildings promote the use of renewable energy sources and encourage the renovation of existing buildings to make them more sustainable. By implementing these measures, the EU is taking significant steps towards a more climate-friendly and energy-efficient future.

The experiences from the European Union have demonstrated that adoption of energy efficiency policies can play a crucial role in reducing energy consumption and subsequent emissions from the building sector. It is noteworthy that those lessons learnt and experiences are making a meaningful contribution in Nepal through the BUILDING Energy Efficiency in Nepal (BEEN) project, funded by the European Union under the SWITCH-Asia Grants Programme.

In the same line, the *Manual on Application of Building Insulation Materials*, prepared by the BEEN project, is expected to contribute to reducing skill gaps and developing skilled human resources. This knowledge product will provide valuable information and guidance to architects, builders and practitioners to incorporate thermal insulation materials in design and construction, thereby reducing energy demand for space conditioning in buildings.

The Manual will be helpful to enhance their understanding and knowledge of the fundamental principles of heat exchange in buildings, thermal insulation materials and the key factors to consider when selecting and applying insulation materials in buildings. Application of building insulation materials offers a range of benefits that can improve the comfort and value of a building in addition to energy efficiency. However, to fully realise these advantages and promote the widespread adoption of sustainable and energy-efficient building practices, effective policy measures are essential.

Overall, the lessons learnt and the best practices of the BEEN project shall have a lasting impact, especially by contributing to the elaboration and adoption of evidence-based policies. Also, by promoting the practices set in motion by BEEN, we hope to roll out the benefits of the energy-efficient measures in homes and buildings throughout the country, ultimately contributing to Nepal's ambitious Nationally Determined Contributions targets and the Sustainable Development Goals agenda.

Finally, I would like to express my sincere gratitude to all project stakeholders, particularly the Government of Nepal, the private sector participating in the project and especially the team of professionals of the BEEN project, for their invaluable contributions to this knowledge product.

....

Jose Luis VINUESA-SANTAMARIA
Head of Cooperation
Delegation of the European Union to Nepal
Kathmandu, 25 September 2024

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Message

The Manual on Application of Building Insulation Materials has been developed under the BUILDING Energy Efficiency in Nepal (BEEN) project. I am thrilled to reach out through this manual to professionals dealing with energy efficiency aspects in buildings and other stakeholders concerned, including academics and insulation service providers. This manual compiles learning from research and experience of Nepalese and international experts from India and Austria on the building physics in relation to insulation. I am delighted to highlight the joint efforts put in by these experts to develop this manual.

Increasing energy prices, concerns over environmental impact, and occupant health and comfort are the factors driving energy-efficient buildings. Adopting appropriate energy-efficiency measures can contribute to creating comfort conditions in buildings while reducing energy use. Thermal insulation contributes to achieving energy efficiency in buildings.

Thermal insulation in buildings is an important but largely overlooked factor in achieving comforts for its occupants. In Nepal, not much attention has been paid to the thermal insulation of buildings from the energy efficiency perspective. This manual has been developed to bridge the knowledge gaps that exist with respect to various insulation materials and to generate awareness among architects and designers, emphasizing the importance of proper insulation in building design and construction.

Proper insulation in buildings starts with a careful consideration of the mode of heat transfer and the direction and intensity in which it moves. This may alter throughout the day and from season to season. It is important to select an appropriate design as well as the correct combination of materials and building techniques to suit particular situations. Thus, the chapters are designed accordingly, starting with the basics of heat exchange in buildings, types of insulation materials, important factors to consider while selecting the insulation material and its application.

We sincerely hope that this manual will be useful to all stakeholders in the building design and construction industry in Nepal, help in the dissemination of basic knowledge about different kinds of insulation materials available to the stakeholders and contribute to future energy saving.

Warm regards,

DI Dr. techn. Daniel Neyer
Project Leader (BEEN)

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Abbreviations

AAC	Aerated Autoclaved Concrete
DBT	Dry Bulb Temperature
DDH	Discomfort Degree Hours
EPS	Expanded Polystyrene
GI	Galvanized iron
HCFC-CFC	Hydrochlorofluorocarbons
kg/m3	Kilogram per cubic metre
mm	millimetre
PIR	Polyisocyanurate
PUR	Polyurethane
RCC	Reinforced Cement Concrete
XPS	Extruded polystyrene

Background

1.1 Need for Insulation Materials

1.2 Need for Thermal Insulation in Energy-Efficient Buildings

Background

1.1 Need for Insulation Materials

The application of insulation in buildings is as old as the building construction activity itself. Prehistoric people built their shelters and dwellings with the same materials that they used for clothing to protect themselves from extreme climatic conditions. The most common materials were animal skins, fur, wool, and natural plant-related materials, like reed, flax and straw. However, these materials had limited durability. With the beginning of agriculture, humans looked for more durable materials for their dwellings, such as wood, combined with earth and stones. This was followed by many naturally-obtained materials, which were suitably processed and used for insulation to improve thermal comfort in homes. The modern-day insulation materials are contemporary adaptations of these earlier products.

1.2 Need for Thermal Insulation in Energy-Efficient Buildings

Buildings can be designed to provide their occupants with thermal and visual comfort while consuming minimal energy. In hot climates, the external surfaces of the building envelope which are particularly exposed to direct solar radiation, such as the roof and walls, heat up at temperatures higher than the outside temperature. The heat is then transferred through thermal conduction to the inner surfaces of the roof and walls, creating an unwanted heat source inside the building. The heat gets distributed inside the building further through radiation and convection, causing discomfort to the occupants. To mitigate this, good air circulation, ventilation and space cooling must be ensured, usually achieved by energy-driven electrical fans and air-conditioning systems.

On the other hand, in cold climatic regions, the heat loss in buildings mainly occurs through transmission from roofs, walls and windows. In addition, ventilation and leakages in the envelope (infiltration) from warmer interiors to cooler exterior can cause heat losses. If these heat transfers are not controlled efficiently, excessive heating will be needed to maintain indoor temperature, leading to high costs and low thermal comfort.

Good thermal comfort at low energy cost can be obtained by adopting energy-efficient building designs. This involves incorporating thermal insulation materials, combined with other building materials, when constructing the building envelope.

Basics of Heat Exchange in Buildings

2.1 Building Envelope: An Introduction
2.2 Importance of Building Envelope
2.3 How a Building Exchanges Heat with its Surroundings
2.4 Thermal Properties of Building Materials

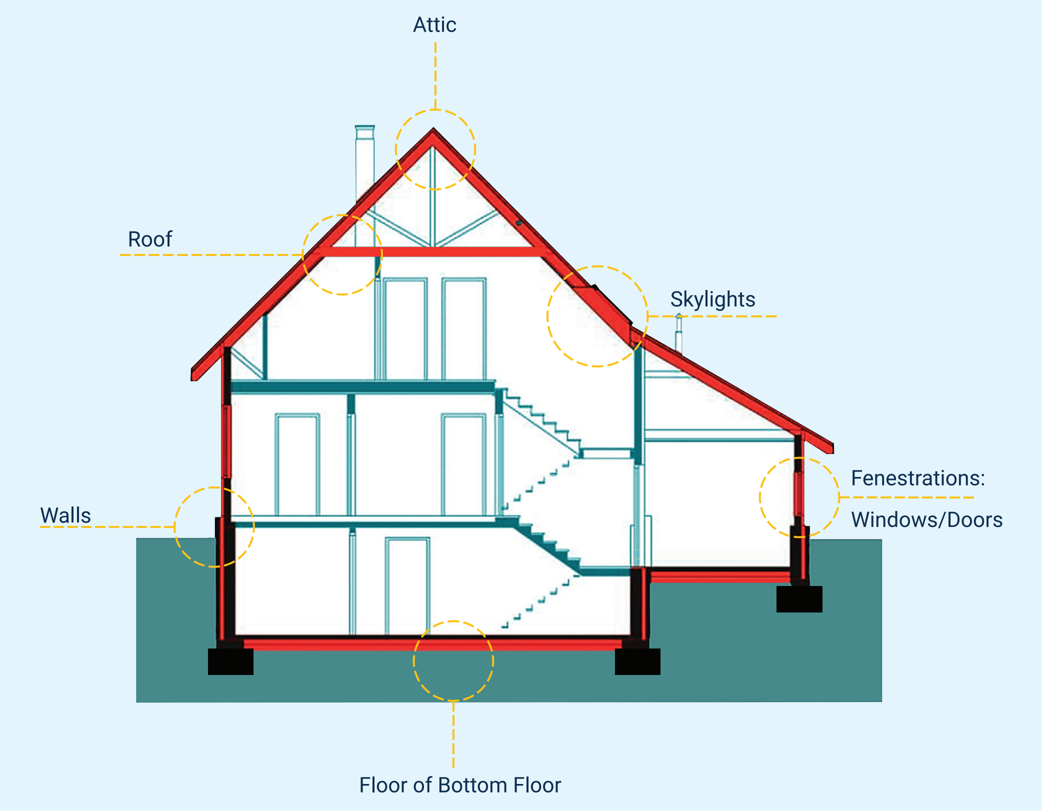
Basics of Heat Exchange in Buildings

2.1 Building Envelope: An Introduction

The part of any building that physically separates the exterior environment from the interior environment is called the building enclosure or building envelope.[1]

The building envelope consists of external walls, roof, windows and doors on the building façade, foundation and floor of the bottom floor, as shown in Figure 1.

Figure 1: Components of a building envelope[2]



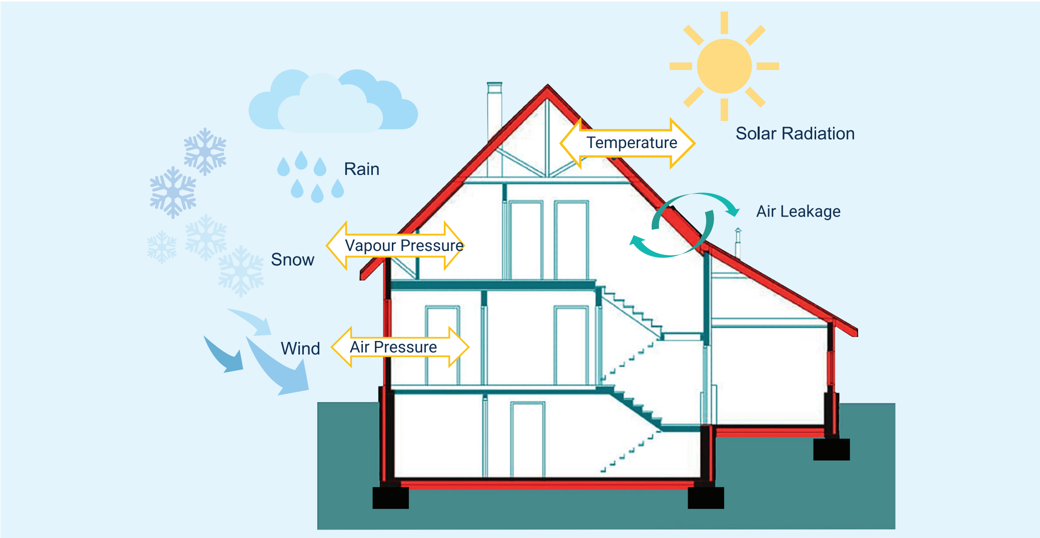
[1] https://buildingscience.com/documents/digests/bsd-018-the-building-enclosure_revised

[2] https://energyeducation.ca/encyclopedia/Building_envelope

2.2 Importance of Building Envelope

The building envelope serves multiple functions. It provides physical protection, shields against rain and noise, controls light and helps in controlling the indoor climate in the building by regulating the heat and air exchange with the exterior environment.

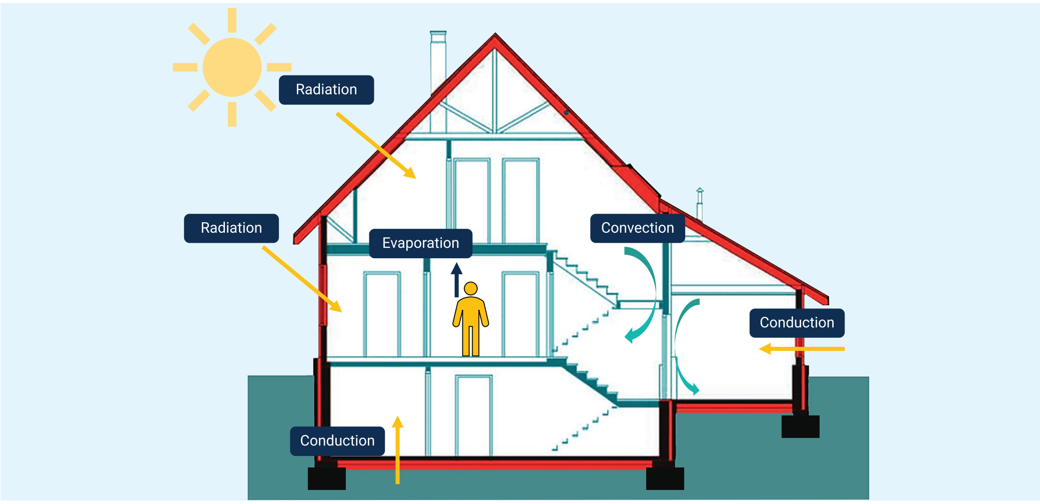
Figure 2: Protection from external elements through building envelope



2.3 How a Building Exchanges Heat with its Surroundings

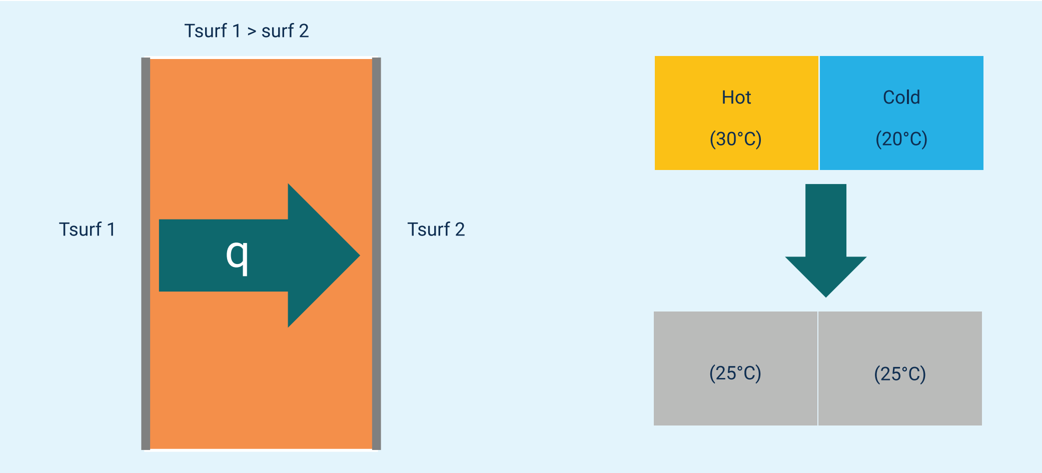
The exchange of heat between a building and its surroundings takes place primarily in three ways: conduction, convection and radiation.

Figure 3: Heat exchange mechanisms in buildings



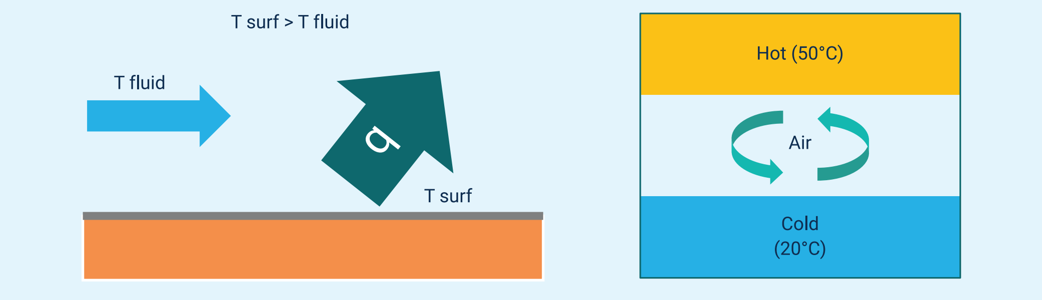
Conduction is the diffusion of internal heat through solid materials due to a temperature difference across them. It is one of the primary heat transfer mechanisms in buildings. For example, during a typical summer, when the outside temperature of the surface of roof and walls is higher than the inside surface temperature, heat flows from the outside to the inside through the roof and wall assemblies by conduction. Conversely, during winters or in cold climates, when the inside surface temperature of the roof and walls is higher than the outside surface temperature, heat flows from the inside to the outside.

Figure 4: Heat exchange through conduction



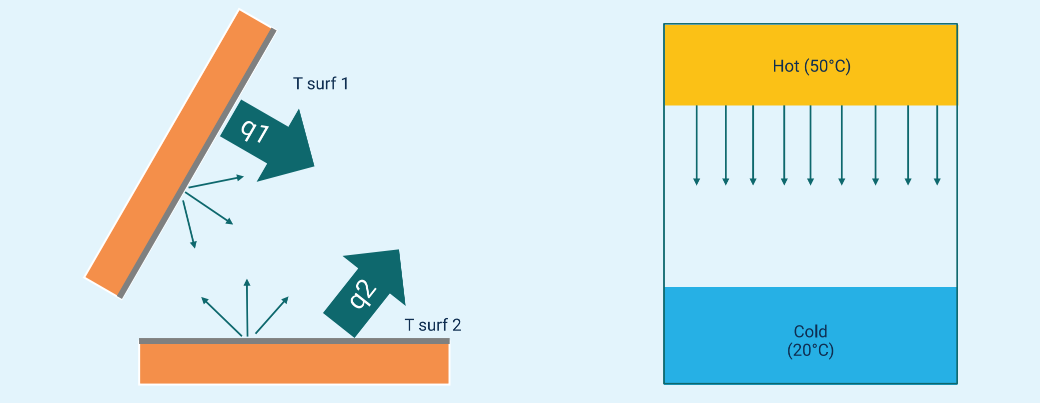
Convection is the process by which heat is transferred by the movement of a fluid, such as air. For example, when the indoor temperature of a building is higher than the outside ambient temperature, open windows allow cooler air to flow through the space and flush out the heat stored in the building, thus cooling the building. This is an example of convective heat transfer.

Figure 5: Heat exchange through convection



Radiation is the movement of heat through space as electromagnetic waves. The sun's energy reaches Earth through radiation. An example of heat transfer through radiation is the heat gained in a building through direct solar radiation falling on a glazed surface. Additionally, all surfaces that emit radiation also absorb radiation emitted by other surfaces. So, all walls, including internal walls, and even human bodies, exchange radiative energy with each other. The radiation of a body always has a range of wavelength. Both the wavelength and the energy emitted by radiation increases with temperature. All objects with temperature above absolute zero (0 K or –273° C) emit radiation at a rate proportional to the fourth power of their absolute temperature (T4 with T in Kelvin). As the surface of the sun is very hot (around 5000 K), sun's radiation is shortwave and includes the visible wavelength, which our brains translate to colours. The far colder surfaces of buildings, humans and surroundings emit longwave radiation.

Figure 6: Heat exchange through radiation



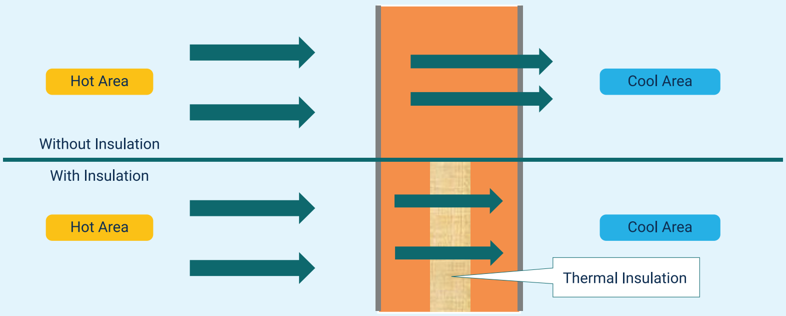
The impact that a building's special layout, choice of building materials and construction techniques has on the various modes of heat transfer through each envelope element is significant. The heat transfer in buildings through the three key elements of building envelope, i.e walls, windows and roofs, predominantly occurs through conduction and radiation. The use of low-conducting building materials and re-organizing spaces can significantly minimize heat transfer through both these modes.

Building insulation reduces heat transfer through conduction in the building envelope. In cold climates, insulation material increases the inside temperature and decreases the outside temperature of walls, minimizing heat exchange through conduction. The application of insulation materials in walls and roof can significantly improve thermal comfort of buildings and improve energy efficiency in buildings.

Figure 7: Effect of thermal insulation in buildings

The Science:

- Heat always flows from hot temperature to cooler temperatures
- Insulation materials do not transfer heat well; thus, reduce heat transfer



2.4 Thermal Properties of Building Materials

The thermal properties of building insulation materials that influence heat transfer in buildings are:

1. Thermal conduction (k-value) indicates the ability of a material to conduct heat. Materials with low thermal conductivity do not easily allow heat to pass through them. A material with a low k-value has good insulation properties, helping keep the building cool.

2. Thermal resistance (R-value) refers to a material's ability to resist heat transfer at a specific thickness. When selecting a building insulation material, materials with a high R-value are preferable as they resist heat transfer more effectively. While the k-value deals solely with the material, the R-value refers to both the material and its thickness. The R values of the different layers in a wall can be simply summed up to the total R-value.

3. Thermal transmittance (U-value) assesses the rate of heat loss through a given thickness of a building element, such as a roof, wall or floor. Materials with a low U-value are preferred, since they gain a small amount of heat in any given time. The U-value of a wall assembly is the reciprocal of its total R value.

Box 1: Other Material Properties

When selecting an insulation material for a building, in addition to its thermal properties, the following factors should be considered as per the National Building Code of Nepal and/or other relevant standards:

» **Fire properties:** The ability of any insulation material to withstand fire is dependent on two key factors:

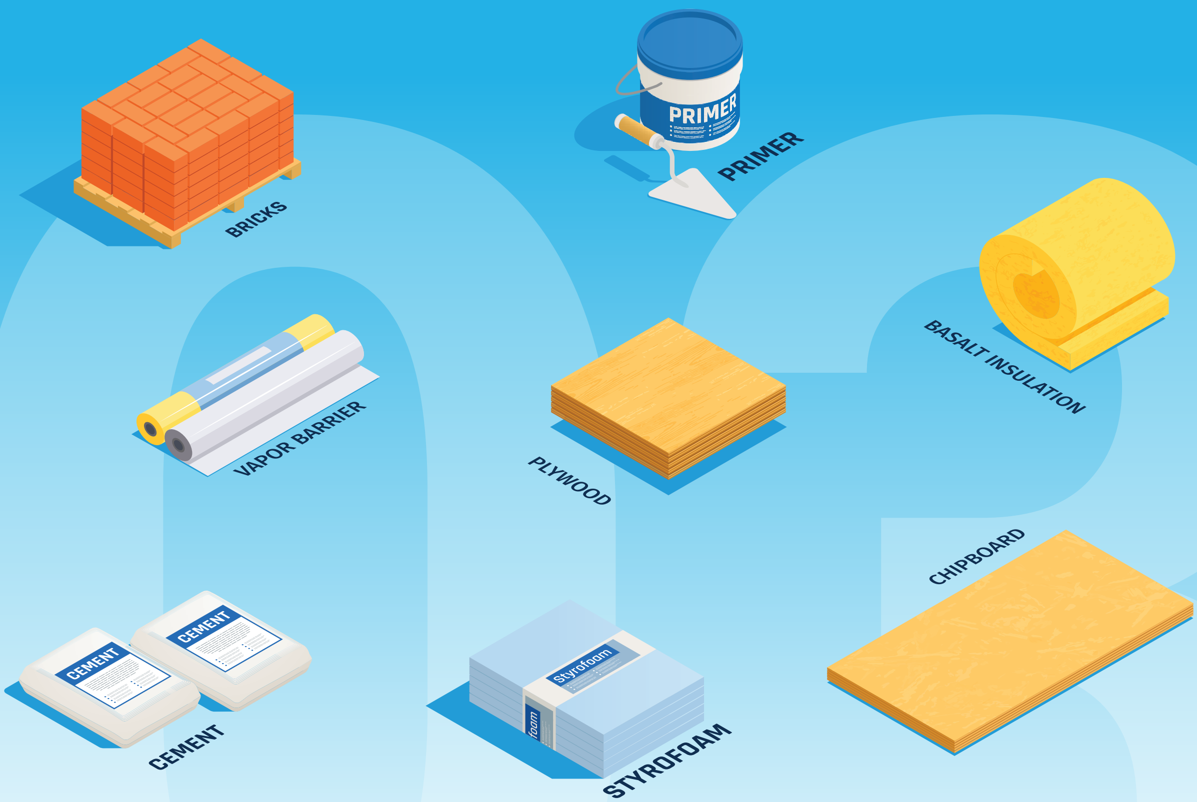
- Reaction to fire indicates whether the material supplies fuel to the fire before the flashover. This classification system is composed of seven groups, ranking from A1 to F, with A1 being non-combustible and F being highly flammable products.
- Fire resistance is the capacity of a construction element or system to maintain its load-bearing function, integrity and thermal insulation properties during a specific period. A good insulation product should have high fire resistance.

» **Mechanical strength:** For certain types of insulation, good mechanical strength under compression (eg in very cold climates, overdeck roof insulation or insulation below the house) and good tensile strength parallel to faces are needed.

» **Water resistance:** Low water absorption by immersion, floatation or vapour diffusion is necessary in wet areas or when the insulation is applied outdoors. The μ-value characterizes the water vapour diffusion property. It represents the ratio of the diffusion coefficients of water vapour in air and in the building material and has, therefore, a simple interpretation. It is the factor by which the vapour diffusion in the material is impeded, as compared to the diffusion in stagnant air. For very permeable materials, such as mineral wool, the μ-value is thus close to 1, whereas it increases for materials with greater diffusion resistance. Water-repellent products that pass the 48-hour water spray test should be used.

- **Dimensional stability** is needed for flat roofs, where the temperature between day and night may significantly vary.
- **Resistance to high temperature** is necessary for flat roofs with a soldered watertight layer and other high temperature applications.
- **Environmental impact:** The embodied carbon impact of the insulation material (kgCO_2 eq/kg) from cradle to gate life cycle stages (A1–A3).

Thermal Insulation Materials



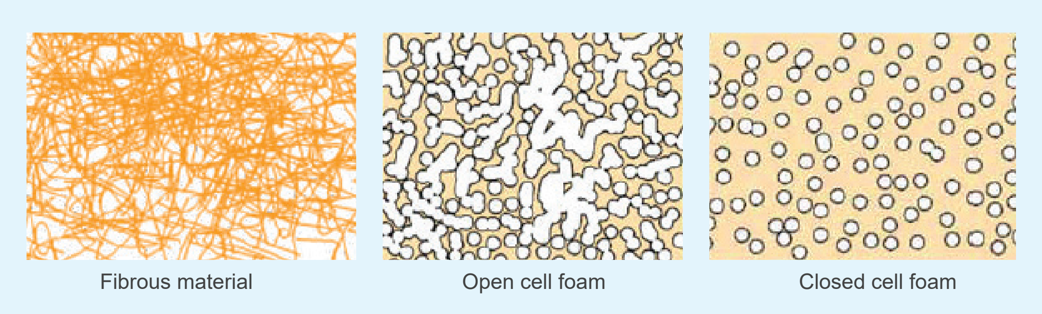
Thermal Insulation Materials

Thermal insulation refers to the use of insulation materials having low thermal conductivity in the building envelope to reduce the rate of heat transfer and its corresponding loss and gain. Compared to liquids and solids, gases and air are poor thermal conductors and, therefore, make good insulation materials.

> For example, the thermal conductivity of air at 35° C is 0.026 W/m-K, which is 20 to 30 times lower than the thermal conductivity of most common building materials. The thermal conductivity of a gas like Argon is almost 30 per cent lower than that of air, which makes it a better insulating gas.

Insulation materials are generally low-density materials within which air or any other gas is trapped, as illustrated in Figure 8. In an insulation material, the flow of entrapped air or gas must be restricted to reduce heat transfer by natural convection. Some insulation materials have air trapped in small cells. In fibrous insulation materials, the fibres within the material add friction to the movement of air and, thus, reduce the convection of heat.

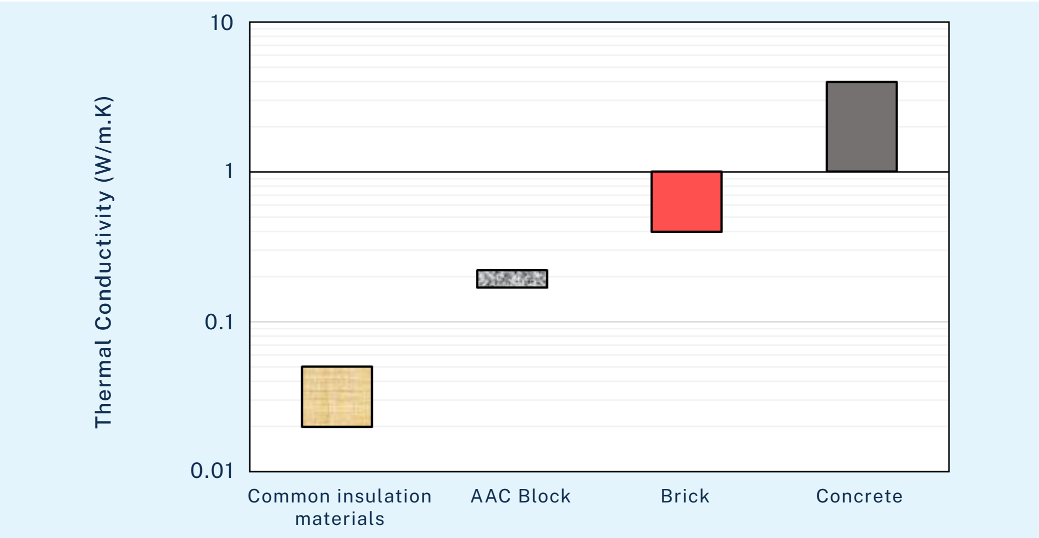
Figure 8: Trapped air or gases in different insulation materials



To ensure that industrial thermal insulation contains sufficient gas cells, glass and polymer materials are inserted to trap air or gas in a foam-like structure, as shown in Figure 8. The same principle is applied in making insulation products from glass wool, mineral wool and other artificial insulators, such as plastic foams. A comparison of common insulation materials used in buildings with some other materials, like aerated autoclaved concrete (AAC) blocks, clay-fired bricks and concrete, is shown in Figure 9.

Natural materials, such as hemp and straw, can also be processed and used as insulation material.

Figure 9: Comparison of thermal conductivity of common insulating materials with some other building materials



3.1 Classification of Building Insulation Materials

Building insulation materials can broadly be categorized into three types: conventional, state-of-the-art and cellulose or natural (as shown in Figure 10).

Figure 10: Classification of building insulation materials

Conventional

- Inorganic materials (mineral wool, rockwool, glasswool, foam glass, vermiculate, etc.
- Organic materials (polystyrene, polyurethane, cellulose, cork, etc)

State-of-the-art

- Aerogel
- Pre-fabricated insulated panels

Cellulose/Nature Based

- Recycled paper/denim-cellulose
- Agro-based/Forest residue products (coconut fibre, straw, bamboo fibre, hemp fibre, etc)
- Sheep wool

- **Conventional insulation materials:** These materials are derived from inorganic materials, like rockwool, mineral wool and glass wool, as well as organic insulation materials, like polystyrenes and polyurethane. They are readily available. Organic materials are usually derivatives of petroleum products or organic materials, like cellulose and plant-based cork. A brief description and key properties of the main conventional building insulation materials are given in Table 1.
- **State-of-the-art insulation materials:** New insulation products, these have superior properties and are commercially available in the market. These include materials like aerogel and vacuum-insulated panels.
- **Cellulose or natural materials:** With an increasing emphasis on sustainable building practices, there is a growing trend towards using natural fibres as insulation materials. These include recycled products like paper in cellulose insulation, plant-based materials like coconut fibre, bamboo fibre and hemp, or animal-based materials like sheep wool. The embodied carbon of such materials is significantly lower than that of conventional building materials.

Box 2: Some key conventional building insulation materials

Inorganic Materials

Glass wool

Glass wool is made from extremely fine glass fibres and arranged into a wool-like texture by using a binder. The process traps many small pockets of air between the glass, which ensures high thermal insulation. Glass wool is normally available in three different forms: blanket (batts and rolls), loose-fill and rigid boards.

Properties

- Thermal conductivity: 0.03–0.05 W/m.K
- Reaction to fire: A1 (non-combustible, no contribution to fire)
- Water vapour diffusion resistance factor (μ): 1–1.3
- Health problems due to fibres damaging to lungs. It is not used in Europe any more.

Mineral wool

Mineral wool typically refers to two types of insulation materials:
- Rockwool, which is an artificial material consisting of natural minerals, like basalt or diabase
- Slag wool, which is an artificial material from blast furnace slag (the scum that forms on the surface of molten metal).

Properties

- Thermal conductivity: 0.033–0.04 W/m.K
- Reaction to fire: A1 (non-combustible, no contribution to fire) and A2 (limited combustibility, very limited contribution to fire)
- Water vapour diffusion resistance factor (μ): 0.5–1.3

Expanded polystyrene (EPS)

EPS is composed of small beads of polystyrene that are fused together. Polystyrene is a colourless and transparent thermoplastic material. Thermocol is an example of expanded polystyrene foam.

Properties

- Thermal conductivity: 0.029–0.041 W/m.K
- Reaction to fire: E (combustible, high contribution to fire)
- Water vapour diffusion resistance factor (μ): 20–100

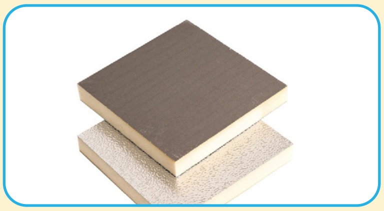
Extruded polystyrene (XPS)

XPS is also made of polystyrene, in which molten polystyrene is pressed out of a form into sheets.

Properties

- Thermal conductivity: 0.032–0.037 W/m.K
- Reaction to fire: E (combustible, high contribution to fire)
- Water vapour diffusion resistance factor (μ): 80–170

Polyisocyanurate (PIR)



PIR or poly-iso is a thermosetting type of plastic closed-cell foam that contains a hydrochlorofluorocarbon-free (non-HCFC) gas of low conductivity within its cells. PIR insulation is available as liquid, sprayed foam and rigid foam board.

Properties

- Thermal conductivity: 0.018–0.023 W/m.K
- Reaction to fire: B (combustible, limited contribution to fire)
- Water vapour diffusion resistance factor (μ): 55–150

Polyurethane (PUR)

It is a foam that contains a gas of low conductivity within its cells. Polyurethane foam is available in closed-cell and open-cell configurations. In closed-cell foam, the high-density cells are closed and filled with a gas that helps the foam to expand and fill up the spaces around it. Open-cell foam cells are not as dense and are filled with air, which gives the insulation a spongy texture.

Properties

- Thermal conductivity: 0.018–0.023 W/m.K
- Reaction to fire: D to F (combustible, medium to high contribution to fire)
- Water vapour diffusion resistance factor (μ): 50–100

Cellulose or Nature Based[3]

Hemp

Hemp insulation is manufactured using hemp wool. Hemp wool is made from strong and woody fibres derived from a hemp plant.

Properties

- Thermal conductivity: 0.039 W/m.K
- Reaction to fire: E (combustible, low to medium contribution to fire)
- Water diffusion resistance factor (μ): 1–10

Cellulose

Cellulose insulation is a plant fibre and is used in walls and roofs for insulation purposes. Modern cellulose insulation is made from either 75 to 85 per cent ground-up recycled paper or recycled denim.

Properties

- Thermal conductivity: 0.040 W/m.K
- Reaction to fire: B (combustible, limited contribution to fire)
- Water diffusion resistance factor (μ): 3

Straw

Straw bales are made from waste products. Once the edible part of the grain, such as wheat or rice, has been harvested, it is compressed to make insulation panels.

Properties

- Thermal conductivity: 0.057 W/m.K depending on density
- Reaction to fire: B (combustible, limited contribution to fire)
- Water diffusion resistance factor (μ): 3–11

3.2 Properties of Conventional Insulation Materials

Table 1 provides a comparison of the key properties of some commercially-available building insulation materials, as discussed in Section 4. Each insulating material has its own advantages and disadvantages. For instance, while glass wool and mineral wool have high fire resistance, they have high moisture and water vapour diffusion similar to air. Conversely, materials like XPS, PUF and PIR have good water vapour diffusion resistance as well as good compression and traction strength but relatively poor fire resistance properties. These differences in properties have an impact on the

3 Thermal properties taken from insulation providers' websites

choice of insulation material for different applications. For example, glass and mineral wool are commonly used in underdeck roof insulation and internal insulation of walls. In contrast, XPS and PUR are more suitable for overdeck roof insulation because they are water resistant due to their closed pores and have high compression strength, making them durable enough for people to walk or even build houses on them. However, all insulation materials need to be protected against birds because they like to build nests on them.

Table 1: Comparison of some key properties of common building insulation materials

Insulating materials	Insulating power	Fire resistance	Water vapour diffusion	Resistance to water	Compression strength	Traction strength	Heat resistance
Dense mineral wool	Very high	Very high	Very low	Medium	Medium	Low	Very high
Organic material	Very high	Medium	Very low	Medium	Very low	Very low	High
PUR	Very high	Medium	Low	Medium	High	High	Very high
EPS	High	High	High	Medium	High	High	Medium
XPS	Very high	High	Very high	High	High	Very high	Medium

Very high | High | Medium | Low | Very low

3.3 Cellulose Insulation Materials

Cellulose comprises thermal insulation made from recycled paper or wood fibre mass. The production process gives the insulation material a consistency somewhat similar to that of wool. Certain additives are added to improve the product properties, such as fire resistance, and to protect them from moulds and pests. Cellulose insulation is used as a filler material for various cavities and spaces and also for the production of cellulose insulation boards and mats. The typical thermal conductivity values of cellulose insulation are between 0.040 and 0.050 W/(m.K)[4]. However, the value varies with temperature, moisture content and mass density.

Cellulose insulation products may be perforated and also cut and adjusted on site without any loss of thermal resistance. While cellulose is a low-cost natural insulation material, it has a high water absorption rate.

[4] Bjørn Petter Jelle, in *Start-up creation: The smart eco-efficient built environment,* 2016, Pp 129–181

3.4 Natural Insulation Materials

Natural or bio-based insulation materials include hemp, straw, wool and fleece. Such materials generally have heterogeneous anatomical and chemical compositions and are susceptible to various decay and staining organisms, weathering, moisture and fire. The degradation agents themselves as well as the exposure conditions are also highly variable; therefore, determining the performance of bio-based building materials is a major challenge.

The thermal performance of bio-based building insulation materials predominantly depends on two factors: long-term stability and performance when wet. Most insulation materials collapse completely as soon as they become wet. Even if dried again, their porous structure cannot be fully restored.

Of the various natural insulation products available, hemp insulation is considered the most practical. Made of hemp wool, it is considered to be similar to mineral wool in terms of both thermal performance and composition. Hemp insulation can maintain its thermal performance even after absorbing moisture up to 20 per cent of its weight. Its R-value ranges from 1.28 m^2k/W to 6.41 m^2k/W, depending on its thickness[5].

[5] https://www.intpetro.com/wp-content/uploads/2015/08/NatuHemp_Brochure.pdf

Factors to Consider When Selecting Building Insulation Materials

Factors to Consider When Selecting Building Insulation Materials

4.1 Placement of Insulation Materials

The placement of insulation materials in buildings, ie on the internal or external side of a wall or roof, has a considerable influence on the dynamic behaviour of the building component and, in some climates, on possible condensation issues.

» **External insulation:** It is recommended to use insulation on the outside surface of walls or roof, not only in cold climates but also in tropical climates. When insulation is applied on the external surface of walls, the thermal inertia of the masonry wall helps to stabilize the indoor temperature. No moisture problems occur as long as the insulation material and cover outside the insulation allows vapour diffusion. The external insulation should be protected from weather and shocks by covering it with a protective layer, which can be a finishing, cladding or even a relatively thin wall. Typical temperature profiles in case of external insulation are shown in Figure 11.

Figure 11: Typical temperature profiles with external insulation

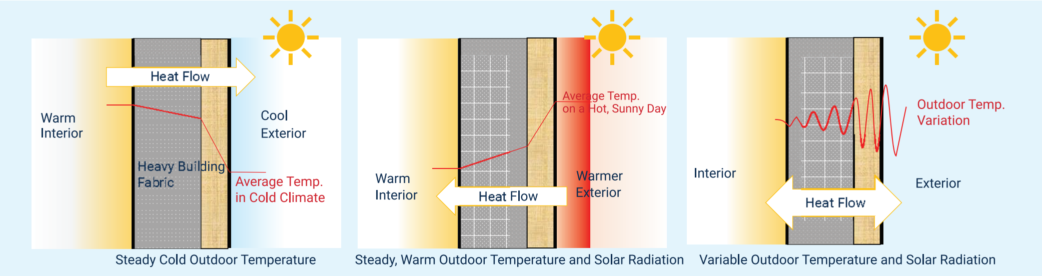
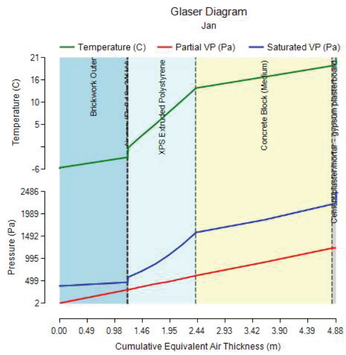


Figure 12 illustrates the Glaser diagram of a wall composition with external insulation in cold climates. Besides showing the temperature profile for the location in the month of January, it shows the movement of vapour pressure, both partial and saturated, in case of external insulation, along the wall's cross section, drawn as the cumulative equivalent air thickness for moisture transport (∑ (thickness * μ) = Sd).

The diagram indicates that the partial pressure is below the vapour pressure in all places; therefore, no condensation or moisture occurs in the wall.

Figure 12: Glaser diagram of external wall insulation in cold climate



» **Internal insulation:** In internal insulation, the insulating layer is placed inside the bearing structure. It is generally protected by a thin internal wall of plaster or wood board. Figure 13 depicts the typical temperature profiles with internal insulation.

Figure 13: Typical temperature profiles with internal insulation

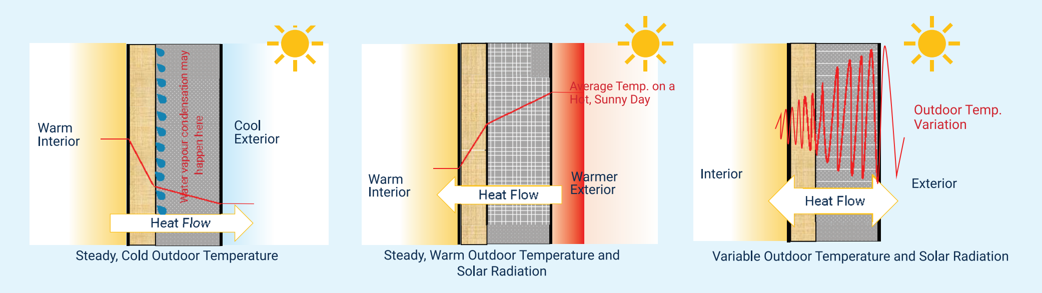
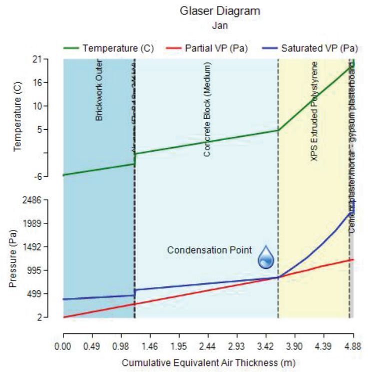


Figure 14 shows the Glaser diagram of a wall composition with internal insulation in cold climates. Besides the temperature profile for the location for January, it shows the movement of both partial and saturated vapour pressures in case of internal insulation. This is likely to result in condensation, leading to infusion of moisture in the insulation layer. This can cause moulds and other problems.

Figure 14: Glaser diagram of internal wall insulation in cold climate



4.2 Insulation Placement in Roofs

In the conventional flat roofing slabs, insulation is placed between the vapour barrier and the waterproofing layer. The waterproof layer can be protected from the sun by a layer of sand and gravel or tiles. The insulation can then withstand compression and high temperature that may occur because of either the sun or the sealing by torch for welding the bituminous layer.

An alternative technique is to use an inverted roof, in which case the thermal insulation is placed above the waterproof layer directly placed on the slab. This slab is often covered with a cement layer to provide a slope. Gravel or concrete plates load insulation plates, protecting them from the sun and preventing them from being dislodged by wind. If the material is waterproof, such as EPS or XPS, it absorbs no or very little water during rains and dries completely. This technique is also suitable for improving the thermal insulation of an existing roof that has a waterproofing membrane in a good state.

Table 2: Comparison between external and internal insulation

Parameter	External Insulation	Internal Insulation
Time Constant	• Increases the time constant of the building, thereby protecting the indoor environment from external temperature variations. • Reduces heating and cooling loads.	• Decreases the time constant. • Increases heating and cooling loads and, therefore, the size of the heating and cooling devices.
Thermal Mass	• Allows using the thermal mass of the building to store excess cold or heat or recover stored heat or cold.	• Does not utilize the thermal mass of the building.
Thermal Bridge	• If it completely covers the outside surface of the building and the window frames partly, it suppresses most thermal bridges.	• Leaves thermal bridges, especially at windows and uninsulated beams and columns.
Vapour Condensation	• Suppresses the possibility of condensation in cold climates; however, the possibility increases slightly in warm and humid climates.	• There is high risk of vapour condensation in cold climates.
Dilatations and Deformations	• Stabilizes the temperature of the structure and, in turn, prevents dilatations and deformations.	• Leaves the outer building structure exposed to external variations, leading to damage and deformations.
Application and Cost	• Needs proper and good quality application, leading to higher cost.	• Low application cost, if applied only partly. • High cost if a complete tight moisture barrier is attached at the inside.

4.3 Insulation in Floors

In case of extremely cold climate, floors may also need to be insulated to prevent heat loss through them. This can be done by tightly packing high-density rigid or fibrous insulation materials below the floorboards. Since both the floor and insulation in this assembly are susceptible to dampness from the ground, proper waterproofing must be done.

4.4 Parameters to Consider When using Insulation Materials

To be effective, thermal insulation in buildings should be applied in conjunction with other passive measures. For example, in hot climates, in case the outside temperature is lower than the indoor temperature, insulation materials should be used only after ensuring that the building has effective solar shading of windows and good natural ventilation. In cold climates, thermal insulation with passive solar heating enhances insulation.

It is also recommended that insulation be applied on both roof and walls, except in warm and humid climates where only roof insulation may suffice. In harsh climates with sub-zero temperatures, insulation should also be applied on the lowest floor, even up to 50 cm into the ground.

It is always better to use thermal insulation on the outside of a building because it protects the envelope from the outside climate and makes the inside space comfortable and the space-conditioning efficient. However, in smaller buildings like residential houses, application of insulation materials inside may be easier, given practical limitations, but they need to be carefully mounted with a good moisture barrier to avoid mould.

There are a few other factors that need to be considered while selecting and applying the insulation material.

4.4.1 Thermal Bridges

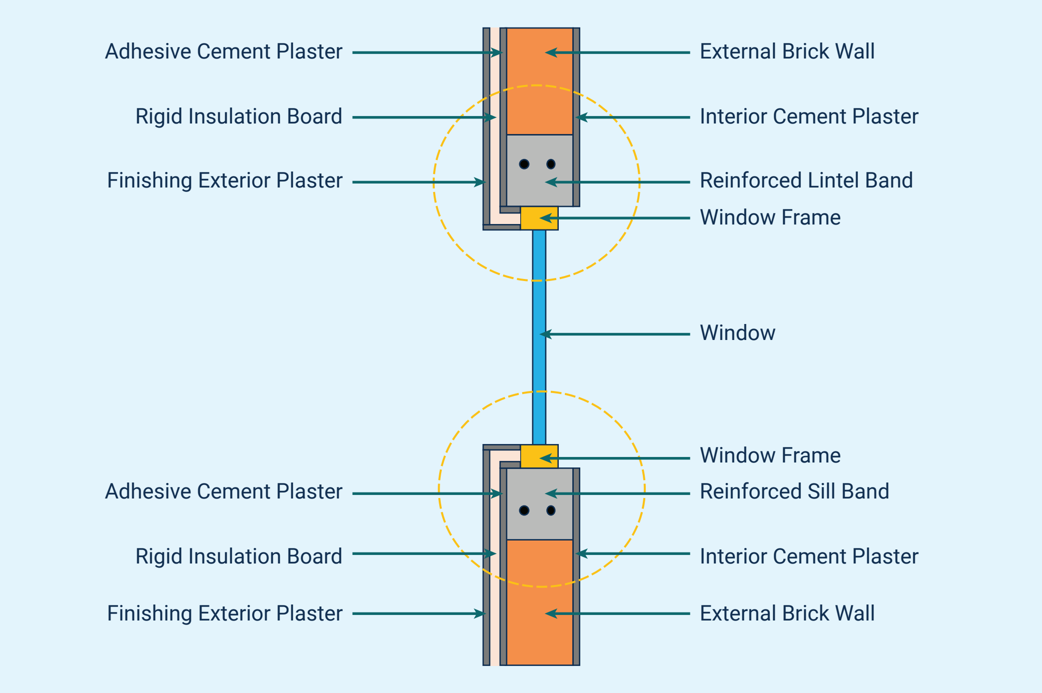
Thermal bridges are pathways through which heat or cold can cross from the inside of a building to the outside or vice versa through the floor, walls and roof components. They reduce the effectiveness of insulation and can also lead to condensation issues. Penetration of elements through the façade, such as concrete balconies through the insulation layer, disruption to the insulation layer due to connections of the building and the roof or frames of elements like windows, can act as thermal bridges, particularly in cold climates. Metal framing is particularly problematic due to its high conductivity. Windows and doors, especially those with aluminium frames that cannot be thermally broken, can also act as thermal bridges.

Thermal bridging in buildings can be minimized by:

- Using external insulation;
- Installing thermal breaks between metal frames and cladding;
- Fixing prefabricated insulated panels over frames; and
- Using thermal breaks in aluminium doors and window frames or less conductive framing materials, like timber or UPVC.

A common practice in the Nepali construction is the introduction of concrete sill and lintel bands for doors and windows, primarily to ensure strength against high seismic activity. These bands also act as thermal bridges and can promote high heat loss in extreme cold regions. Therefore, wall insulation should be applied in a way that minimizes thermal bridges. Figure 15 illustrates how the insulation material can envelope the window frame to break the thermal bridge.

Figure 15: Section of a typical wall with window showing the insulation application to minimize thermal bridges through the sill and lintel bands



4.4.2 Vapour Barrier

Most building materials, such as bricks, are permeable to water vapour diffusion. In cold climates, water vapour diffusing through the wall can condense on colder surfaces, eg the outer face in winters. To prevent condensation issues, the finishing of this face must be permeable to water vapour. A vapour barrier is any material used for damp proofing, typically a plastic or foil sheet, that reduces or hinders diffusion of moisture through the wall, floor, ceiling, or roof assemblies of buildings.

The type and application of a vapour barrier depend on various factors, such as the type of insulation and external or internal use of insulation. In the case of fibrous materials like glass wool or rockwool, the material comes packed in a polythene sheet and is applied as it is. In cases where polythene sheets act as a vapour as well as an air barrier and avoid condensation, a snug fit should be ensured. In the case of rigid insulation materials such as PUF, PIR and XPS, the sheets are usually laminated with aluminium foil on one side. The side with the foil is generally placed face down in contact with the RCC (reinforced cement concrete) or bricks. A coat of mastic treatment should be applied on the wall or roof, which also acts as an adhesive for the insulation and also ensures that moisture does not affect the insulation material.

An interior vapour barrier is beneficial in heating-dominated climates with very little or no internal insulation, while an exterior vapour barrier may be advantageous in cooling-dominated warm and humid climates (Figures 16 and 17). Using a Glaser diagram can help determine which material configuration of a surface facing the exterior needs a moisture barrier. As far as possible, a wall construction that can function without a moisture barrier should be chosen.

Figure 16: Concrete block with exterior insulation and brick or stone veneer: heating-dominated climates

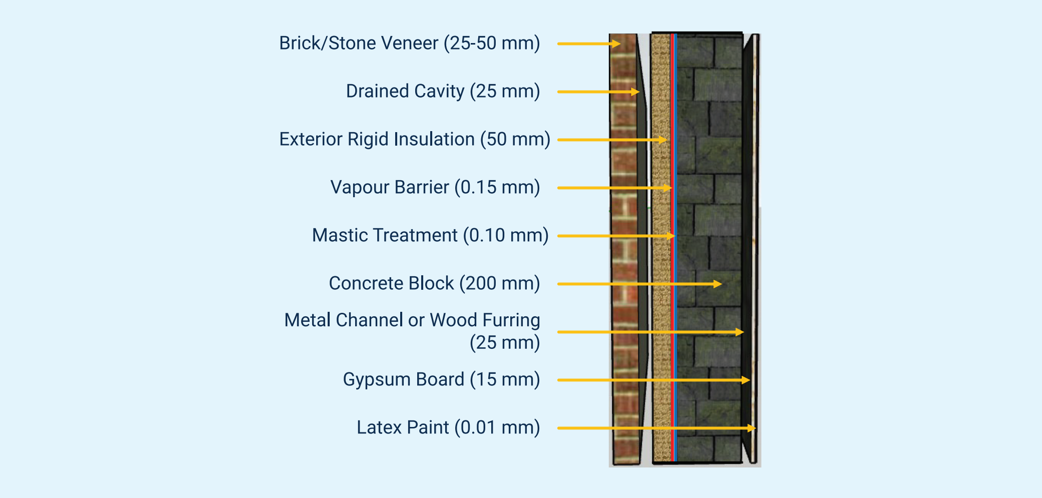
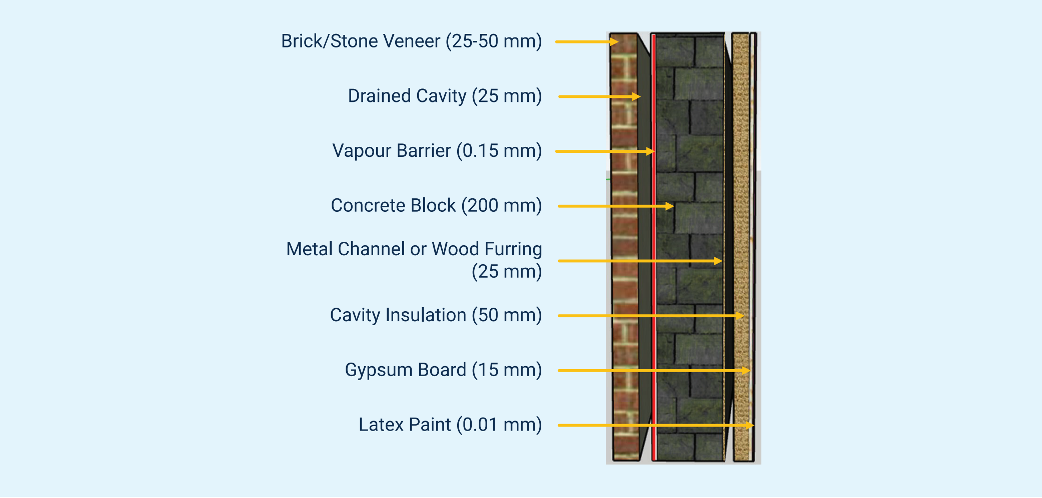
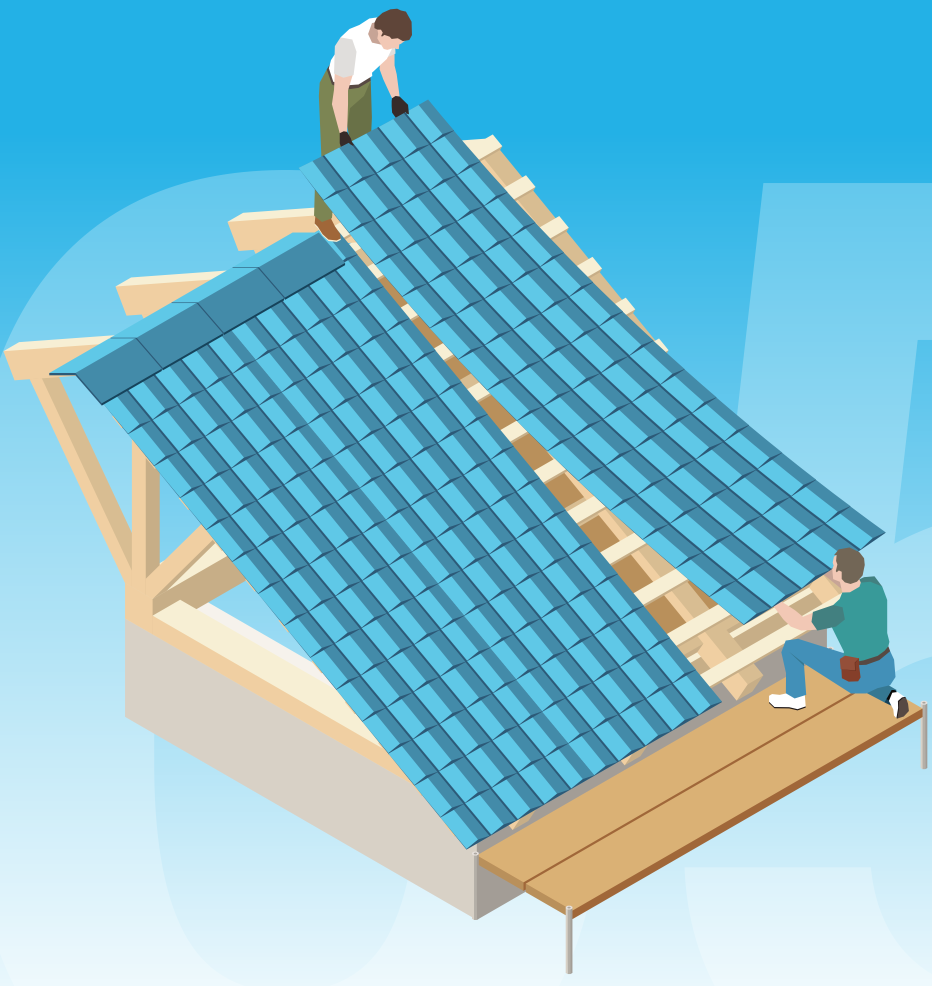


Figure 17: Concrete block with interior frame wall cavity insulation and brick or stone veneer: cooling-dominated climates



Application of Insulation Materials

5.1 Roof Insulation



Application of Insulation Materials

This section elaborates how to apply insulation materials on roofs and walls, providing combinations based on various placements, methods and materials.

5.1 Roof Insulation

5.1.1 Overdeck Roof Insulation

a) Rigid Board Slab Insulation

STEP 01 Ensure that the roof slab is totally dry and free from all protrusions and depressions. It should have proper slope for free flow of water (1:100).

STEP 02 Provide suitable waterproofing over the sloping screed.

STEP 03 Lay rigid PUF or PIR or XPS foam insulation slab or board of minimum 32–40 ± 2 kg/m density and specified thickness. The insulation can be fixed with suitable adhesives, like hot bitumen or rubber-based bituminous adhesive compound, as optional.

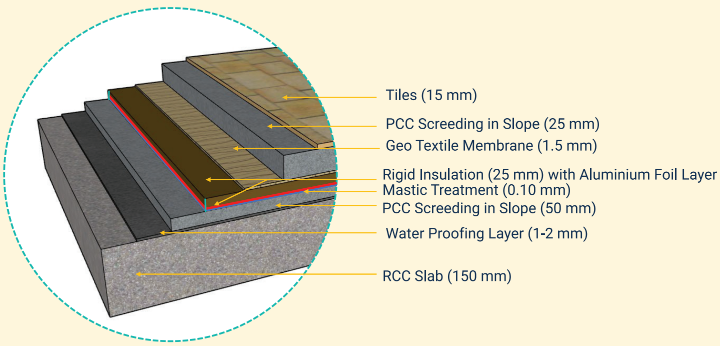
STEP 04 Lay a minimum of 150 gsm geo-textile membrane or 400-gauge polythene sheet over the fixed insulation slab or board as a protection and separation layer.

STEP 05 Over the protection layer, lay a layer of at least 40mm thick PCC (1:2:4) in chequered 2.5 m x 2.5 m panels with a slope gradient, reinforced with welded mesh of 75 mm x 75 mm x 1.5 mm embedded in between.

STEP 06 Seal all joints between panels with polymerized mastic.

STEP 07 Apply final finish as per specifications or as directed by the engineer-in-charge.

Figure 18: Overdeck roof thermal insulation system



b) Inverted Roof[6]

STEP 01 Ensure that the roof slab is totally dried and free from all protrusions and depressions. It should have proper slope for free flow of water (1:100).

STEP 02 Provide suitable waterproofing over the sloping screed.

STEP 03 Apply a mastic asphalt waterproofing layer.

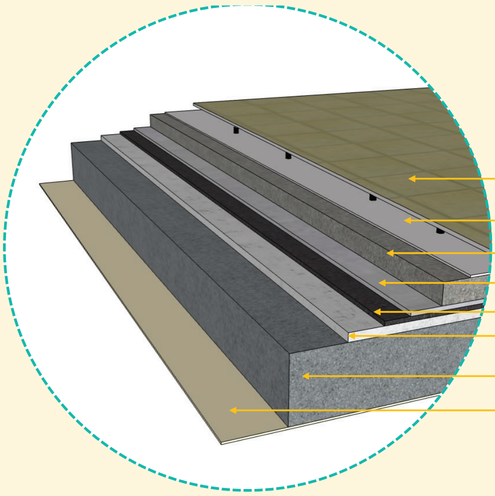
STEP 04 Lay a minimum 400-gauge polythene as a separation layer.

STEP 05 Lay rigid PUF or PIR or XPS foam insulation slab or board of minimum 32–40 ± 2 kg/m^3 density and specified thickness. The insulation can be fixed with suitable adhesives like hot bitumen or rubber-based bituminous adhesive compound, as optional.

STEP 06 Lay a layer of 300 mm geo-textile membrane to reduce water flow and prevent water from reaching the insulation.

STEP 07 A layer of washed, low fines, rounded and gravel ballast between 16 mm and 32 mm in size should be carefully placed directly over the system at a minimum thickness of 50 mm.

Figure 19: Inverted roof system



[6] The materials for insulation applications are mostly sourced from IIF (2015). *Training Manual on Application of Building Insulation.* India Insulation Forum. Available at https://www.indiainsulationforum.in

5.1.2 Underdeck Roof Insulation

a) Fibrous Insulation

STEP 01 Clean the surface thoroughly with a wire brush to free it from dust and chippings.

STEP 02 Fix mild steel cleats of suitable dimensions to the ceiling at 1 m x ½ m centre to centre with the help of dash fasteners.

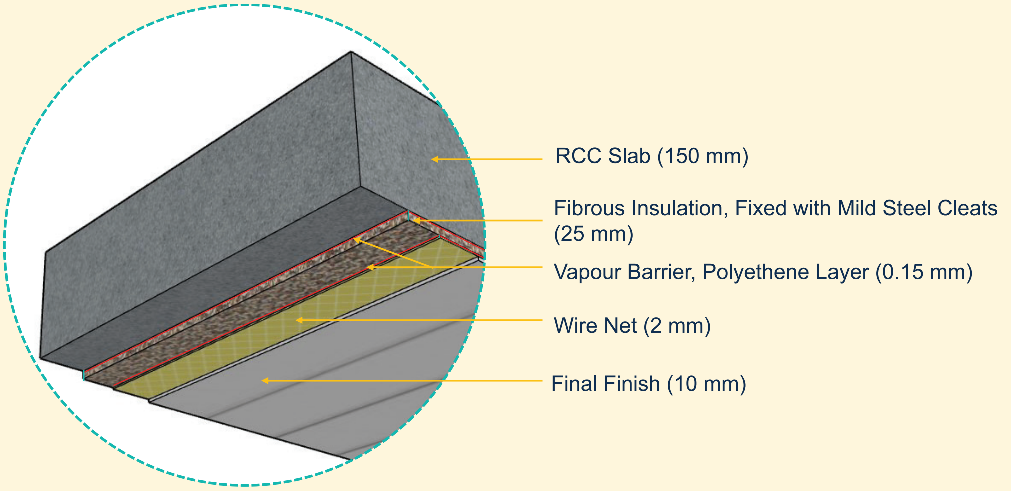
STEP 03 Fix the desired thickness of fibrous insulation (glass wool or rockwool), with a minimum density of 24–48 kg/m^3, encased in a 200-gauge laminated with aluminium foil or polythene sheet on one side.

STEP 04 Seal all joints with an adhesive or aluminium tape and hold them tightly in position with the help of crisscross GI lacing wire and install the same in a hexagonal wire netting.

STEP 05 Ensure that all joints of the wire netting are butted and stitched with GI lacing wire.

STEP 06 Apply final finish as per specifications or as directed by the engineer-in-charge.

Figure 20: Underdeck fibrous insulation



b) Rigid Insulation

STEP 01 Drill holes in the RCC slab with a spacing of 1 m x 0.5 m centre to centre.

STEP 02 Ensure that the RCC surface is thoroughly cleaned of all dust, dirt and loose particles by wire brushing.

STEP 03 Apply a coat of bituminous primer to the bare RCC ceiling and allow it to dry.

STEP 04 Apply a cold adhesive to the underside of RCC ceiling as well as on one face and sides of each rigid insulation of PUF or PIR or XPS (with a minimum density of 32–40 ± 2 kg/m^3). The aluminium foil on the face towards the slab acts as a vapour barrier.

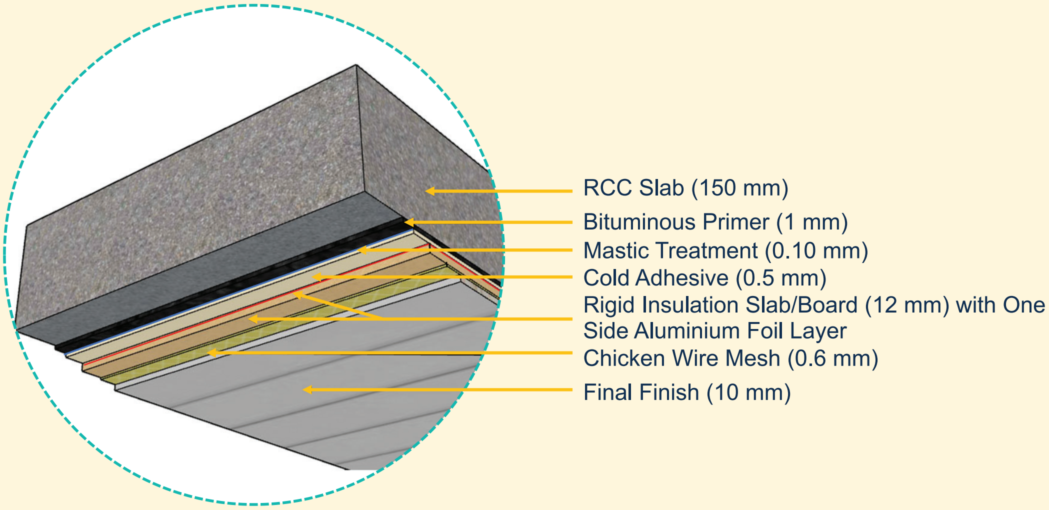
STEP 05 Press it in position, holding it with the help of screws and washers inserted inside the raw plugs.

STEP 06 Seal and butt the joints symmetrically with a 75 mm wide aluminium tape.

STEP 07 Fix a chicken wire mesh, 24 G x 3/4", to the GI screw and tighten the same with lacing wire.

STEP 08 Apply final finish as per specifications or as directed by the engineer-in-charge.

Figure 21: Underdeck rigid insulation



5.1.3 External Wall Insulation

a) Fibrous Insulation behind Dry Stone Cladding

STEP 01 Ensure that the wall surface is clean.

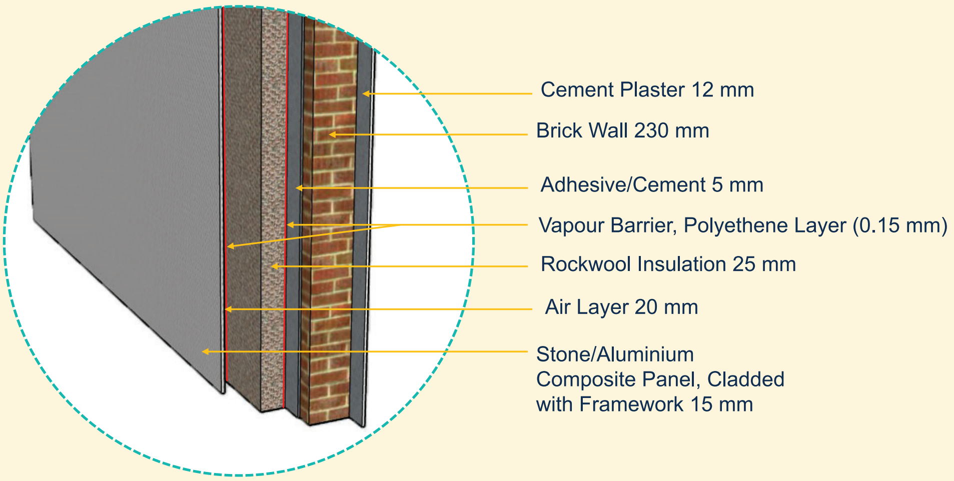
STEP 02 Fix the desired thickness of fibrous insulation glass wool or rockwool, with a minimum 64–96 kg/m^3 density, encased or wrapped in a polythene sheet or bag of 200-gauge or one side laminated with aluminium foil in the existing wall with the help of fasteners. The fasteners should be placed one each at a corner 100 mm away from the edge and one at the centre.

STEP 03 Hold the fibrous insulation in position with crisscross GI lacing wire secured with the fastener fixed earlier.

STEP 04 Insulation can be sandwiched between the wall and the drystone cladding or aluminium cladding, etc as per specifications or as directed by the engineer-in-charge.

A ventilated air layer should be present between the insulation layer and the cladding to evacuate water vapour. It is also useful for evacuating excess heat from the sun.

Figure 22: External wall fibrous insulation behind cladding



b) Rigid Insulation behind Cladding

STEP 01 Ensure that the wall surface is clean and smooth.

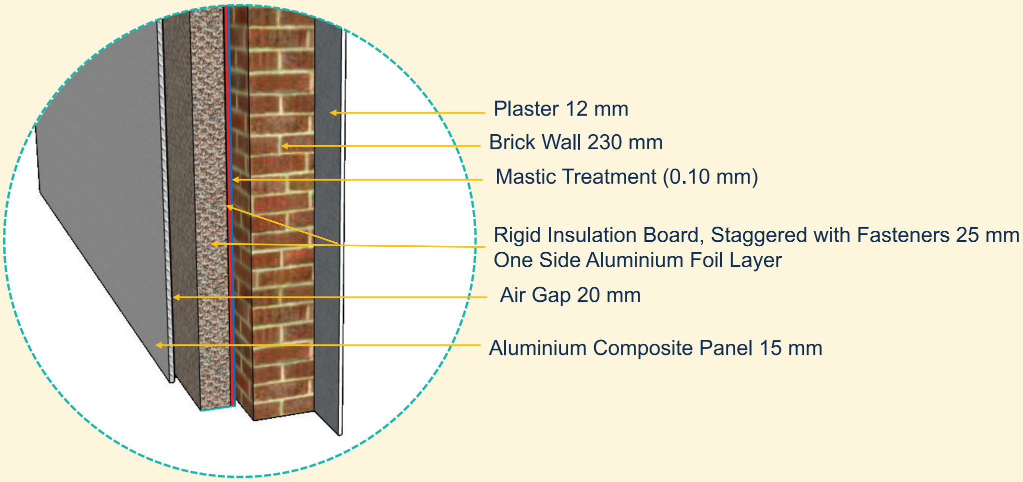
STEP 02 Apply a coat of bitumen or a rubber-based bituminous adhesive compound on to the existing smooth wall.

STEP 03 Fix the rigid insulation PUF or PIR or XPS of desired thickness, with a minimum density of 32–40 ± 2 kg/m^3, in a staggered form using fasteners, one at each corner 100 mm away from edges and one at the centre.

STEP 04 The insulation can be sandwiched between the wall and the dry-stone cladding or aluminium cladding as per specifications or as directed by the engineer-in-charge.

A ventilated air layer should be present between the insulation layer and the cladding to evacuate water vapour. It is also useful for evacuating excess heat from the sun.

Figure 23: **External wall rigid insulation behind cladding**



C) External Rigid Insulation with Finishing

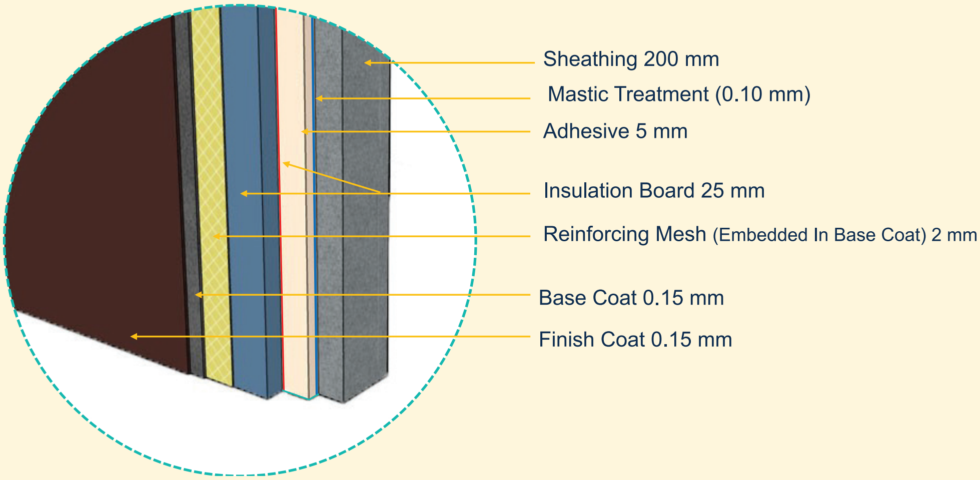
STEP 01 Ensure that the wall surface is clean and smooth.

STEP 02 Apply the polymerized cementation-based adhesive plaster to the back of the rigid insulation, PUF or PIR or XPS, with a minimum density of 32–40 ± 2 kg/m³) in patches, and stick the same surface to the existing plastered or smooth brick walls, holding it with insulation fasteners, one each at the corner.

STEP 03 Apply the cementation-based coat of 1–2 mm over the rigid insulation.

STEP 04 Apply a glass fibre mesh as reinforcement over the base coat, followed by polymerized cementation-based topcoat plaster of 1–2 mm. The topcoat can be finished with any paint of choice as per specifications.

Figure 24: External rigid insulation with finishing



5.1.4 Insulation in Cavity Wall

a) Spray in-situ PUF Insulation

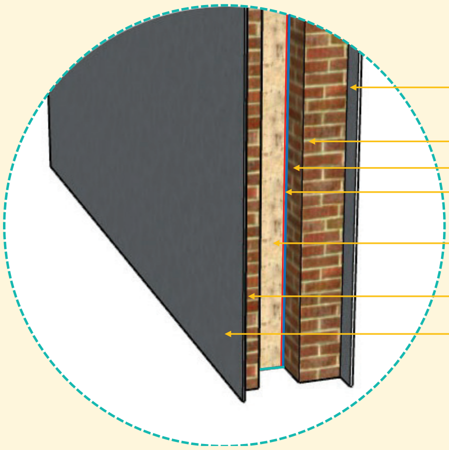
STEP 01 Drill a hole into the inner wall at a distance of 100 mm from the edges and thereafter at every approximate 600 mm centre to centre in a staggered form, starting from the bottom to the top.

STEP 02 Through these holes, pour the in-situ closed cell polyurethane foam (HCFC-CFC-free) in the cavity with a Gusmer/Graco machine. The density of foam should be 42 ± 2 kg/m^3. The foam adheres instantly to the wall surface on both sides and has a free rise, filling the gap or cavity.

The in-situ polyurethane foam insulation should be poured from the bottom and proceed upwards.

STEP 03 Plug the hole with cement mortar or as per specifications.

Figure 25: Spray in-situ insulation



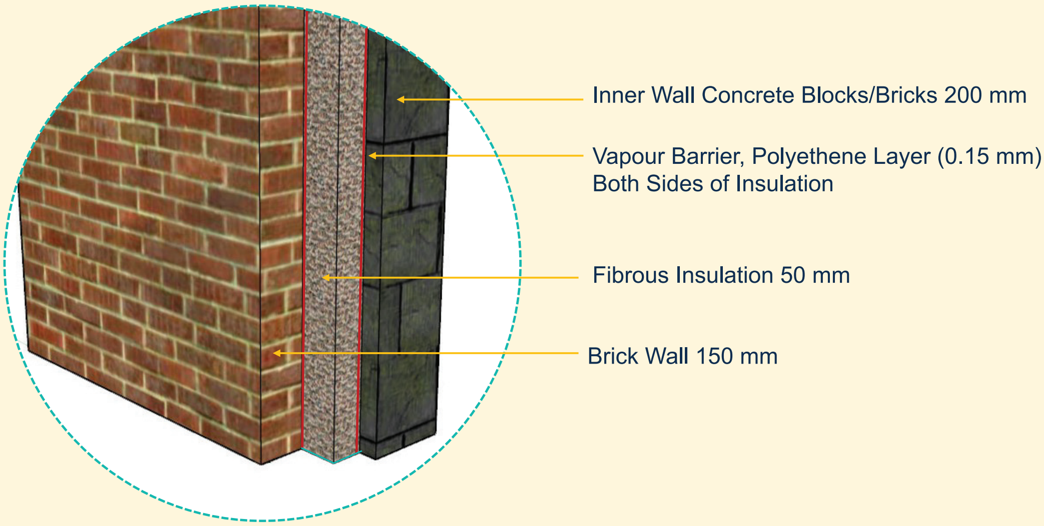
b) Fibrous Insulation

STEP 01 Fix the fibrous insulation glass wool or rockwool of desired thickness, with a minimum density of 64–96 kg/m^3, with one side having a polythene bag of 200-gauge to the inner wall in a staggered form, using fasteners, one each at the corners, 100 mm away from the edges and one at the centre.

STEP 02 Hold the fibrous insulation in position with crisscross lacing wire secured with the fasteners fixed earlier.

STEP 03 Finish it off with another brick wall duly plastered and finished smooth.

Figure 26: Cavity wall insulation with fibrous materials



Application of Insulation Materials

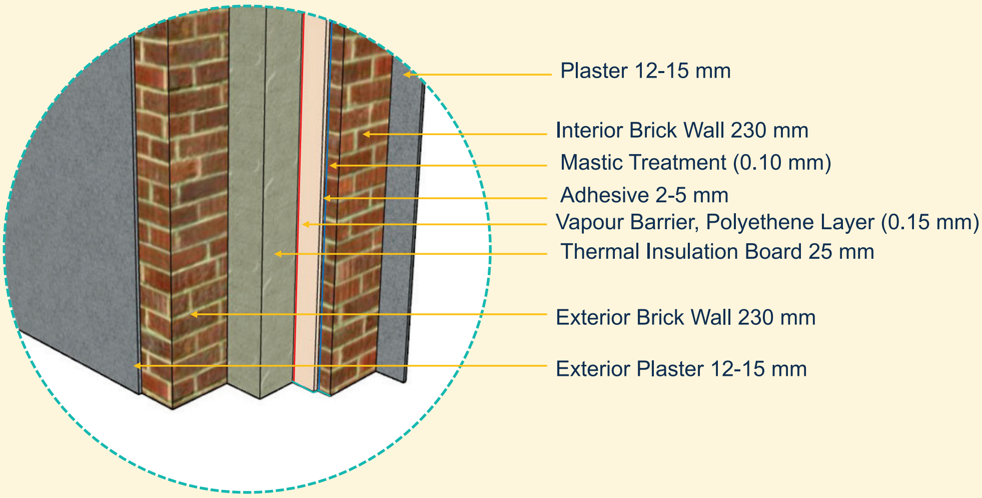
c) Rigid Insulation

STEP 01 Apply a coat of bitumen or a rubber-based bituminous adhesive on the inner side of the inner wall.

STEP 02 Fix the rigid insulation panel PIR or XPS of desired thickness, with a minimum density of 32–40 kg/m³, to the inner wall in a staggered form, using fasteners, one each at the corners 100 mm away from the edges and one at the centre. The insulation board should be laminated with aluminium foil on the face towards the inner layer of the cavity wall.

STEP 03 Finish it with another brick wall duly plastered and finish smoothly.

Figure 27: Cavity wall insulation with rigid foam



5.1.5 Internal Wall Insulation

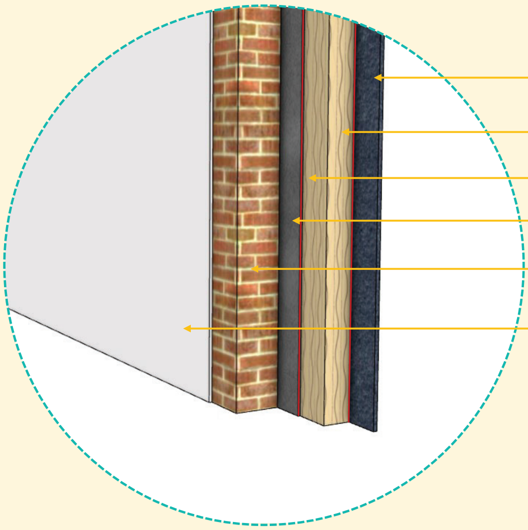
a) Fibrous Insulation

STEP 01 Fix the fibrous insulation glass wool or rockwool of desired thickness, with a minimum density of 64–96 kg/m^3, with one side facing a polythene sheet or a bag of 200-gauge to the inner wall in a staggered form using fasteners, one each at corners 100 mm away from the edges and one at the centre.

STEP 02 Hold the fibrous insulation in position with crisscross lacing wire secured with the fasteners fixed earlier.

STEP 03 Finish it off with the gypsum board and finished smooth.

Figure 28: Internal wall insulation with fibrous materials



5.1.6 Floor Insulation

a) Rigid Insulation below Floorboard

STEP 01 Ensure that the floor slab is totally dried and free from all protrusions and depressions. It should have proper slope for free flow of water (1:100).

STEP 02 Provide suitable waterproofing over the sloping screed.

STEP 03 Lay a minimum of 150 gsm geo-textile membrane as a separation layer.

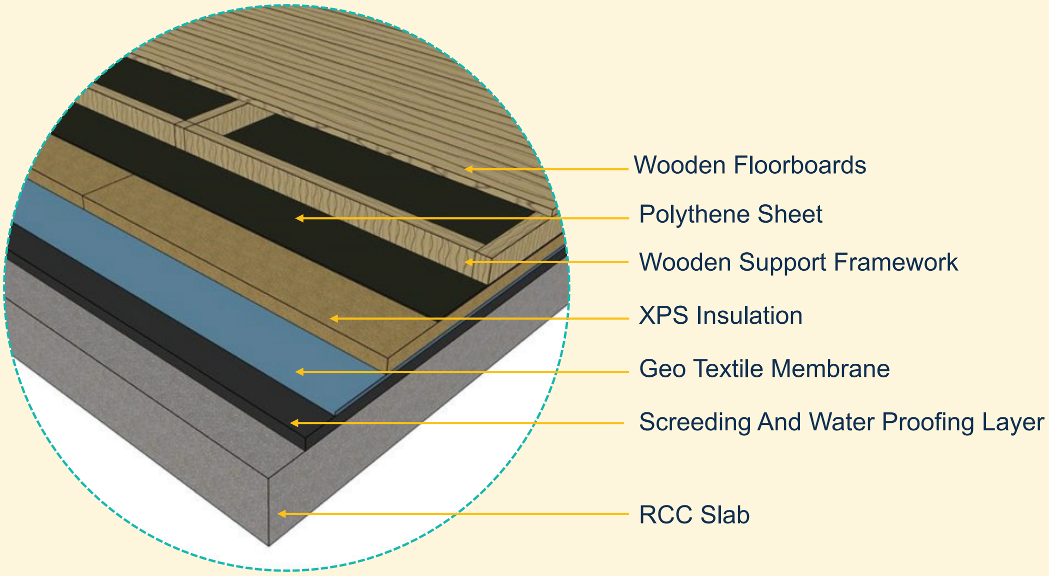
STEP 04 Lay rigid insulation of 130–150 kg/m³ density and specified thickness.

STEP 05 Lay a polythene sheet that acts as a vapour barrier.

STEP 06 Lay the support structure, either wooden or metallic, depending on the final floor.

STEP 07 Lay the final finish (wooden floorboards or any other) as per specifications or as directed by the engineer-in-charge.

Figure 29: Floor insulation below wooden floorboard



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Annexure

Thermal Conduction

The steady state conduction heat transfer rate through a homogenous building material, having a thickness of Δx metre (m), in which the inside surface is maintained at a temperature Ti Kelvin (K) and the outside surface temperature is maintained at To K is given by the following equation:

$$q = \frac{k}{\Delta x}(Ti - To) = \frac{1}{R}(Ti - To)$$

Where,

q is the heat transfer rate in W/m^2

k is the thermal conductivity in W/m-K

Δx is the thickness of the material in m

R is thermal resistance value of the material with thickness Δx in m^2K/W

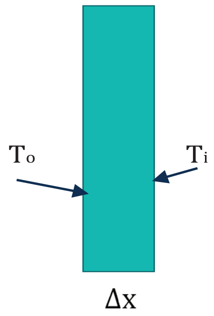
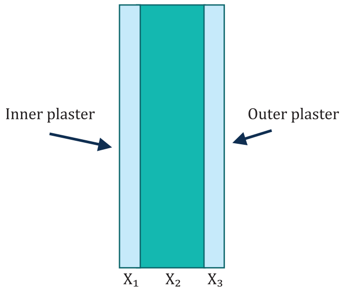


Figure 30 Thermal conduction

Thermal Resistance (R-value)

Any building material's resistance to conductive heat flow is measured or rated in terms of its thermal resistance or R-value. The higher the R-value, the greater the insulating effectiveness of the material. It depends on the material's characteristics, thickness and thermal conductivity. The R-value of a given material is expressed numerically as the ratio of its thickness (Δx) in the direction of heat flow to its thermal conductivity (k). The R-value is expressed in (m^2K/W)

$$R = \frac{\Delta x}{k}$$



In a building envelope, the roof and walls are generally an assembly of several layers of different building materials. Every building material layer contributes and adds to the combined thermal resistance of the roof and wall assembly, depending on its thermal conductivity and thickness.

In Nepal, a common wall assembly is solid clay fired brick wall plastered with cement plaster on both inside and outside. Let us assume that the wall is made of common bricks (thickness x_2 and thermal conductivity k_2), which is plastered on both sides (inner plaster of thickness x1 and thermal conductivity k_1 and outer plaster of thickness Δx_3 and thermal conductivity k_3).

In this case the combined thermal resistance of the composite wall is given by:

$$R_{wall} = \frac{x_1}{k_1} + \frac{x_2}{k_2} + \frac{x_3}{k_3} = R_1 + R_2 + R_3$$

However, in real situations, a thin virtual air layer is also formed on both external and internal surfaces of the roof and walls, which are exposed to the outside and inside temperatures respectively. Due to their temperature differences, these surfaces promote heat transfer in their vicinity through convection and radiation, while, at the same time, resisting heat transfer through roofs and walls. These resistances are termed as 'surface thermal resistance', and they are also added to the thermal resistance of the wall. So, the combined thermal resistance of the composite wall in real situations is given by:

$$R_{wall} = R_{s-int} + R_1 + R_2 + R_3 + R_{s-ext}$$

For calculation purposes, the default values of R_{s-int} and R_{s-ext} are given in Table 3.

Table: Default values of R_{s-int} and R_{s-ext}

	Wall	Roof	
		Warm Climate	Cold Climate
R_{s-int} (m^2.K/W)	0.13	0.17	0.10
R_{s-ext} (m^2.K/W)	0.04	0.04	0.04

Thermal Transmission (U-Value)

In designing buildings, the U-factor, also called thermal transmittance, of a composite wall (or an assembly of walls) and a composite roof (or an assembly of roofs) is generally calculated. In simple terms, this factor is the reciprocal of the total thermal resistance (R) of a composite wall or a composite roof. In practice, a low U-factor is desirable to resist transfer of heat from higher temperature to a lower temperature through roofs and walls.

$$U_{wall} = \frac{1}{R_{wall}}$$

Exercise 1: Calculation of R-value and U-value of typical outer wall and roof assembly in Nepal

Outer Wall: Calculate the R-value and U-value of outer wall assembly made up of 230 mm of common solid burnt clay brick (k=0.6 W/m.K) with inner and outer surface plastered with 15 mm plaster (k=0.72W/m.K).

$$R_{wall} = 0.13 + \frac{0.015}{0.72} + \frac{0.23}{0.6} + \frac{0.015}{0.72} + 0.04 = 0.595\, m^2K/W$$

$$U_{wall} = \frac{1}{0.595} = 1.68\, Wm^2/K$$

Roof: Calculate the U-value of a roof assembly made up of 150 mm RCC slab (k=1.58 W/m.K), 15 mm plaster (k=0.72 W/m.K) on the inner side and 20 mm cement screed (k=0.72 W/m.K) on the outside. The building is located in a cold climate.

$$R_{roof} = 0.10 + \frac{0.015}{0.72} + \frac{0.23}{1.58} + \frac{0.015}{0.72} + 0.04 = 0.284\, m^2K/W$$

$$U_{roof} = \frac{1}{0.284} = 3.53\, Wm^2/K$$

Exercise 2: Calculation of the U-value of a typical outer wall and roof assembly after introduction of a thermal insulation layer

Outer wall: Let us take a case in which an additional layer of 50 mm thick insulation material (k = 0.03 W/m.K) is introduced in the outer wall of Exercise 1. Now, the total thickness of the wall assembly is 280mm.

$$R_{wall} = 0.13 + \frac{0.015}{0.72} + \frac{0.23}{0.6} + \frac{0.05}{0.03} \quad \frac{0.015}{0.72} + 0.04$$
$$= 0.595 + 1.667 = 2.262\, m^2K/W$$

$$U_{wall} = \frac{1}{2.262} = 0.44\, Wm^2/K$$

Roof: Let us take a case in which an additional layer of 50mm thick insulation material (k = 0.03 W/m.K) is introduced in the roof of Exercise 1. Now, the total thickness of the roof assembly is 235mm.

$$R_{roof} = 0.10 + \frac{0.015}{0.72} + \frac{0.15}{0.58} + \frac{0.05}{0.03} \quad \frac{0.02}{0.72} + 0.04$$
$$= 0.284 + 1.667 = 1.921\, m^2K/W$$

$$U_{roof} = \frac{1}{1.921} = 0.52\, Wm^2/K$$

It is observed that the introduction of an insulation material having a low thermal conductivity (k=0.03 W/m.K) and relatively small thickness of 50mm helped in enhancing the thermal resistance of the traditional wall assembly and roof assembly by ~ 400–500%.

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