<u>A review on insulation materials for energy conservation in buildings</u>

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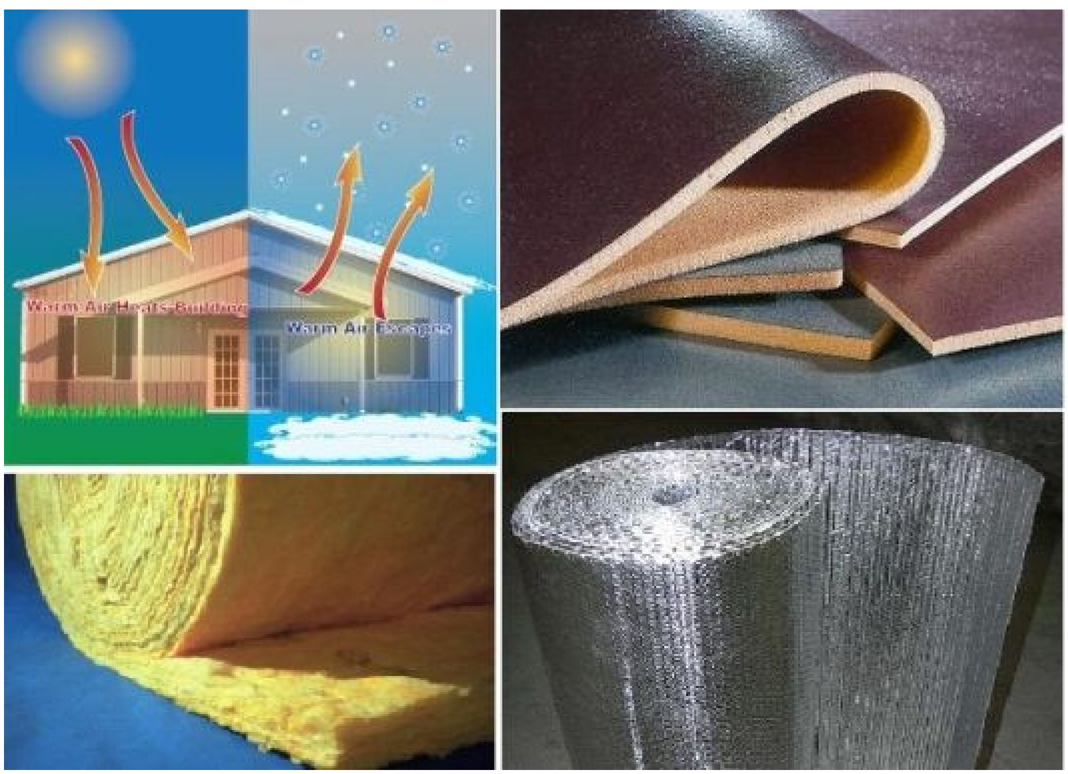

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1 ABSTRACT

In residential sector, air conditioning system takes the biggest portion of overall energy consumption to fulfil the thermal comfort need. In addressing the issue, thermal insulation is one efficient technology to utilize the energy in providing the desired thermal comfort by its environmentally friendly characteristics. The principle of thermal insulation is by the proper installation of insulation using energy-efficient materials that would reduce the heat loss or heat gain, which leads to reduction of energy cost as the result. This paper is aimed to gather most recent developments on the building thermal insulations and also to discuss about the life-cycle analysis and potential emissions reduction by using proper insulation materials.

2 Introduction

Global energy consumption is foreseen to be increased by 53% within the next ten years from the International Energy Agency (IEA) prediction, which is as the result of the significant increase in industrial and urban activities due to the intensive country development and dramatic increase of population size in the recent times. The rising energy demand is expected to be more severe, especially in developing countries due to the rapid growth of new buildings while the use of energy efficiency technologies is often not gaining sufficient attention. As the consequence of the energy demand upsurge, environmental issues are becoming more apparent. As the consequence of the energy demand upsurge, environmental issues are becoming more apparent. Carbon dioxide (CO_2), an instance of the pollutant, has widely known as a harmful substance to human health. Carbon dioxide plays a strong contribution in the greenhouse gas effect. The couple leads to the rising of average global temperature. If no necessary steps are taken to reduce the emissions of $CO_2$and other greenhouse gases, the Earth's average surface temperature is predicted to rise about 1.1–6.4 °C by the end of 2100. A 2 °C increase of the global average temperature would cause irreversible impacts on the environment, severe issue on human health, huge damage on natural ecosystems as well as affecting global agriculture sustainability. As one sector that consumes a vast amount of energy to provide thermal comfort, construction sector in general (residential, industrial and commercial buildings) could contribute to lower its energy consumption through proper, effective insulation strategies. An effec-tive insulation conserves energy and consequently requires less energy for space cooling in summer and less heat to keep the house warm in winter. The chain effect of implementation of this energy efficiency technique reduces the use of natural resources (petroleum and gas reserves) that are used for power generation, and it slows down their depletion rate. Thus, it lowers the greenhouse gases production. Insulation in building is considered as a simple yet highly energy efficient technique that can be applied to residential, commercial and industrial sector. Thermal insulator is composed by a material or composite material that possesses the characteristic of high thermal resistance, which exhibits the ability to decrease the heat flow rate. As a result, building insulation is able to keep the heat/cool within the house and prevent heat flux with the surrounding. Various substances, such as fiberglass, mineral wool, foam and other materials are typically used as an insulator. Another major advantage of building insulation is cost saving. This is feasible since the building insulation contributes to a positive net energy balance through a larger amount of energy saved through the insulation application than the energy required to manufacture the insulation material itself. Furthermore, utilizing thermal insulation brings other benefits, including fire protection, personal comfort, condensation control and sound control. The aim of this paper is to review the state of the art of innovative thermal and acoustical insulating materials from natural and/or recycled materials which development is at an early stage. This paper reports the variety of innovative insulation materials, technical important parameters and material properties in thermal (density, thermal conductivity and specific heat) and acoustic (sound absorption and insulation properties) insulations, brief analysis about fire and vapor resistance, and sustainability of the innovative insulation materials.

3 Classification of building insulation materials

Despite all insulation materials serve the same purpose to reduce the rate of heat release/gain through the desired enclosed space some particular materials serve a certain specific role, hence they are categorized accordingly. These categories classify insulation materials into: according to the function, form and composition.

3.1 According to heat exchange properties

Insulations can be categorized into two main classes per their function in manipulating the heat transfer: mass insulation and reflective insulation. Mass insulations are those that can retard the heat flow by conduction, while reflective insulations are the ones to reduce the amount of heat transfer by radiation.

3.1.1 Mass insulation

Objects with high thermal mass absorb and retain heat, slowing the rate at which the sun heats a space and the rate at which space loses heat when the sun is gone. Without thermal mass, heat that has entered a space will simply re-radiate back out quickly, making the space overly hot with sunlight and overly cold without. Mass insulations are those that can retard the heat flow by conduction. Insulation can be extremely valuable in preventing direct heat gain from being conducted to the ground or outside air, where it is lost. In hot climate where direct heat gain is not desirable, it can even be beneficial for exterior finishing to have low thermal mass, as well as low conductivity, to increase the effectiveness of insulation. Regarded as the most commonly used type of thermal insulation, mass insulation diminishes heat flow rate by conduction at the case where practically no convection and radiation occur by heat transfer. Due to this, the effectiveness of mass insulations is highly depending on insulation material thickness. Increasing the thickness proportionally increases the thermal performance of the mass insulation, and these materials usually have low rate of heat conduction. Apart from that, the thermal performance of thermal insulation material is also depending on the condition of subdivision or density of material. Mass insulation usually contains a huge number of tiny air trapped pockets, which reduces conductive heat transfer. These tiny pockets of trapped air act as barriers for heat flow. Therefore, any attempt to condense or compress the mass insulation will reduce its effectiveness.

3.1.2 Reflective insulations

Reflective insulations are thermal insulation which reflects radiation heat, preventing transfer from one side to another due to rejective (or low emittance) surface. This simultaneously decreases the amount of heat transference or solar heat gain impacting the building and improves interior temperatures and air quality. The amount of energy radiated depends on the surface temperature and a property called emissivity; the higher the emissivity, the greater the emitted radiation at that wavelength. Reflective insulation utilizes one or more low-emittance reflective surfaces that enclose air spaces, which is usually used in home attics, roofing and wall systems. The reflective insulation has at least one reflective surface that faces an airspace by this application. The reflective insulation contributions on the thermal performance detailed were investigated in a number of publications.

3.2 According to form

Loose-fillers spray foam, batts, blankets and rigid board are the four basic types of insulation. There are many factors need to be considered when choosing the insulation, such as construction type, rehabilitation plan and the code requirements. Several authors have presented building insulation material characteristics performance by their form, as shown in Table

١.3.3 According to composition

In general, composition of insulation material indicates the insula-tion characteristics which directly linked to its chemical and physical structure. Papadopoulos classified insulation materials based on their composition, which mainly are organic, inorganic, combined-material and new technology material, as structurally shown in Figure 1.Papadopoulos introduced a precious classification of insulating materials for building applications.

3.3.1 Inorganic and organic materials

Inorganic insulation materials are made from non-renewable materials but from plentiful available resources. Some example of inorganic insulation materials are mineral wool, perlite, aerated concrete blocks and foamy glass. On the other hand, organic insulation materials are derived from natural vegetation and renewable resources, such as wood wool, cellulose, expanded rubber, wood fiber, sheep’s wool, etc. There is an increasing interest in organic insulation materials due to their attractiveness; they are renewable, recyclable, on-toxic, environmentally friendly and require very low resource production techniques. The energy that is required to manufacture organic insulation materials is lesser than that of the traditional insulation materials. However inorganic insulation materials generally higher thermal insulation properties and lower costs for the same thermal performance. Also, they show higher resistance to fire and moisture.

3.3.2 Combined and new technology materials

Combination of insulation materials is a feasible approach to improve thermal performance and energy efficiency at optimized cost. Apart from that, new technology materials have been discovered for the application of thermal insulation system. Nowadays, transparent insulation materials are being used as the replacement of the traditional opaque insulation materials because of their advantage of thermal insulation and solar collection. Besides, the application of dynamics insulation that utilize the ventilation system has been introduced in order to improve insulation performance. Many researches have studied different potential insulation materials for their insulation properties (bulk density, thermal con-ductivity, embodied energy and thermal attribute) and their resistivity to biological threat (insects, pests, etc.), as tabulated in Table 2 The potential material for building insulations.. Additional minor classification of insulation materials is based on the raw resources. Conventional insulation material is derived from petrochemical substances. These insulation materials include fiberglass, mineral wool, polystyrene, polyurethane foam, and multi-foils. These materials are convenient since the raw substances could be processed into many different variants with simple installation. However, unconventional insulation materials offer the environmental threat the conventional insulation materials could cause. Unconventional insulation materials are renewable; they reduce con-sumption of fossil energy and disposal issues. Furthermore, A good insulation material with proper designed is essential for effective energy conservation in buildings. There are Table 1 Performance characteristics of common building insulation materials by their form.

Table 1
Performance characteristics of common building insulation materials by their form.

Form	Material	Density (Kg/m^3)	Thermal conductivity (W/m-K)	Fire resistance	Effect as vapor barrier (% water absorption)	Effect as infiltration barrier	Resistance to direct sunlight	Maximum service temperature (C°)	Durability	Sc ab
Blankets: Batts or Rolls [23]	Fiberglass (sand & recycled glass)	12–56 [29]	0.04–0.033 [29]	✓	–	–	✓✓✓	−4–260°	Compression reduces R-value	↑↑
	Rockwool (natural rocks)	40–200 [29]	0.037 [29]	✓✓✓	–	–	✓✓✓	−240–800°	Compression reduces R-value	↑↑
	Polyethylene	35–40 [29]	0.041 [29]	–	✓✓	✓	✓✓	−40–90°	R-value decreases w/ time	–
Loose-fill blown-in or poured-in [23]	(open cell structure)	10–48 [29]	0.038–0.030 [29]	✓✓	–	–	✓✓✓	−4–260°	Comp. & moisture degrade R-value	↑↑
	Rockwool (open cell structure)		0.040 [29]	✓✓✓	–	–	✓✓✓	−240–800°	Comp. & moisture degrade R-value	↑↑
	Cellulose (ground-up waste paper)	24–36 [29]	0.054–0.046 [29]	✓✓	–	–	✓✓	80°	Comp. & moisture degrade R-value	↓
	Perlite (natural glassy volcanic rock)	32–176 [29]	0.06–0.04 [29]	✓✓✓	✓	✓	✓✓	760°	Good	↓
	Vermiculite	64–130 [29]	0.068–0.063 [29]	✓✓✓	–	✓	✓✓	1315°	Good	↓
Rigid Board [23]	Fiberglass (open cell structure)	24–112 [29]	0.035–0.032 [29]	✓✓	✓	✓	✓✓✓	−4–350°	More rigid than batts	↑
	Expanded Polystyrene (closed cell foam)	16–35 [29]	0.038–0.037 [29]	–	✓	✓	–	100°	R-value decreases w/ time	↓
	Extruded Polystyrene (closed cell foam)	26–45 [29]	0.032–0.030 [29]	–	✓✓✓	✓✓	–	100°	R-value decreases w/ time	↓
	Polyurethane								Good (0.5–1.5%)	↑↑
	Perlite (natural glassy volcanic rock)	32–176 [29]	0.06–0.04 [29]	✓✓✓	✓	✓✓✓	✓✓	760°	High	↓
	Vermiculite (natural mineral)	64–130 [29]	0.068–0.063 [29]	✓✓✓	✓	✓✓✓	✓✓	1315°	V. high	↓
Sprayed-in-Place [23]	Cellulose (waste paper)	24–36 [29]	0.054–0.046 [29]	✓✓	–	✓✓	✓✓	80°		↓
Foamed in- Place [23]	Polyurethane &								Good	↑↑

Figure 1 Classification of the commonly used insulating materials

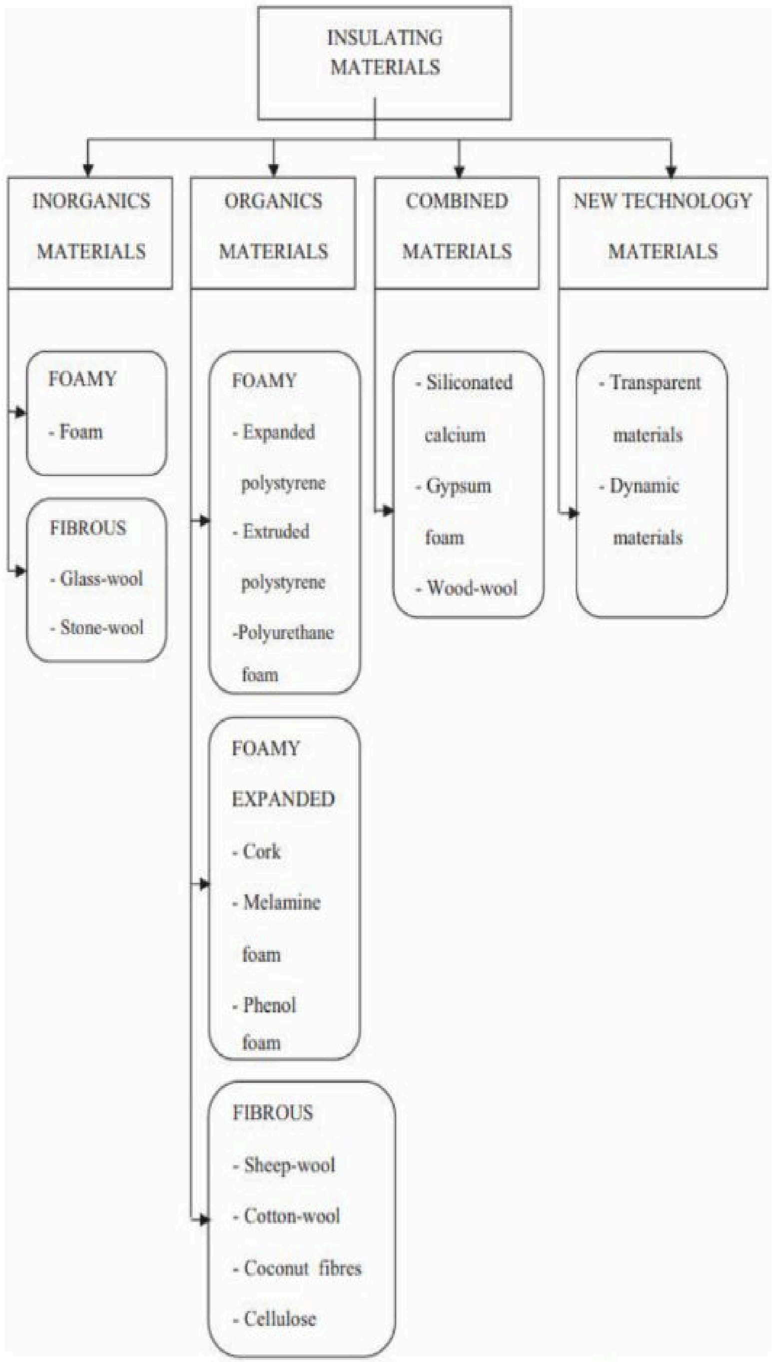


Fig. 1. Classification of the commonly used insulating materials [30].

relevant factors to be considered during material selection, such as cost, durability, climate factor, availability, heat transfer mode, the ease level of installation and building orientation. Combined and new technology materials can be one of a good thermal building insulation material as long as has been designed properly and all the relevant factor are considered. The following materials are the variant of the combined and new technology materials, namely the mineral wool, cellulose, expanded polystyrene (EPS), cork, polyurethane(PUR), extruded polystyrene (XPS) and other building materials such as wood, stainless steel, carbon steel, brick, stone and glass.

4 State-of-the-art thermal building insulation

A lot of extra effort have been given in the development of building insulation materials. The combination of technical innovation and advancement in materials processing technology birth state-of-the-art thermal building insulation. The materials categorized under here are believed by many to provide thermal requirement of building through specific innovatory approaches that are equipped with variance of appealing benefits. This paper reviews several state-of-the-art insulation materials, including closed cell foam, vacuum insulation panel, gas filled panel, aerogel and phase change material (PCM).

4.1 Closed cell foam

High compact insulations, such as the independent foam structure can be established without connection of bubble cell among each other in resin bulk. Bubble cell minimization and foaming gas injection that tends to produce thinner thermal insulation layers have been progress-sing by recent manufacturing technologies, over the past decade. As a result, it enables insulation materials to save the filling space by 40% if compared to glass wool required thickness for an equivalent performance. However, the product has a hard surface that cannot be used to insulate the cavity walls. It would be more useful to insulate external walls and heat bridge shields in applications such as covering the steel frame surface in steel moment frame construction. In the selection of materials for acoustic insulation, the density of the material should be considered because it has an influence on the soundproof abilities. It showed the relationship between the density of the foam wall thickness and width of the hole formed; the wall of cell thicker while the cell diameter gets smaller at the greater density.

Table 2 The potential material for building insulations.

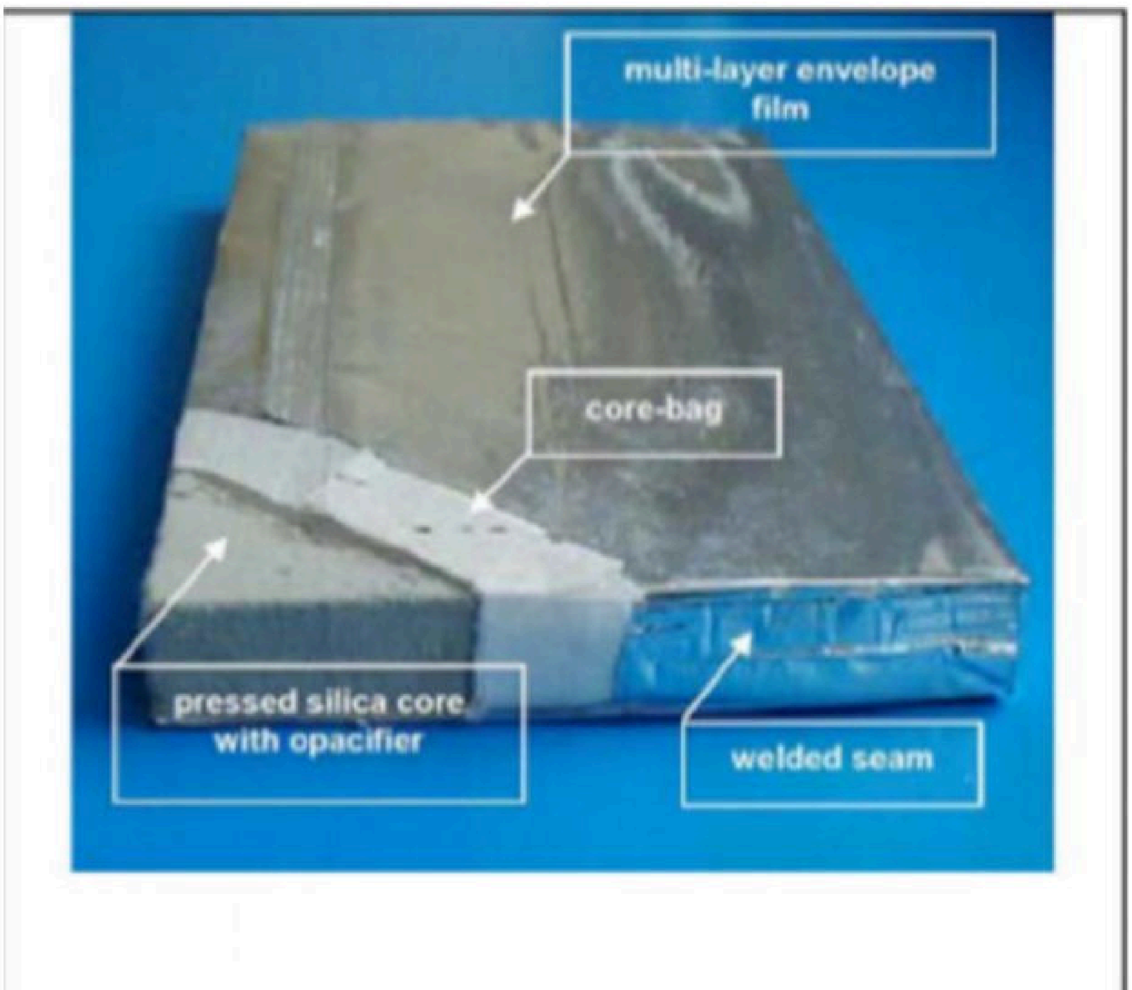
Table 2
The potential material for building insulations.

	Bulk density (kg/m^3)	Thermal conductivity (λ) (W/mK)	Embodied energy kWh/m^3	Thermal attributes	Resistance at biological dangers (Insects, etc.)
Foam			751 [31]	Poor [30]	Good [30]
Glass wool	20–50 [35] 18–50 [32] 10–100 [37]	< 0.040 [35] 0.050 [32]		Average [30]	Good [30]
Stone Wool	5–50 [32] 15–300 [36] 30–60 [32]	0.035–0.071 [32] 0.037–0.050 [36] 0.050 [32]		Average [30]	Good [30]
Expanded polystyrene	18–50 [30]	0.029–0.041 [30]	1125 [31]	Average [30]	Good [30]
Extruded polystyrene	20–80 [30]	0.025–0.035 [30]	1125 [31]	Average [30]	Good [30]
Polyurethane foam	30–80 [30]	0.020–0.027 [30]	1125 [31]	Good [30]	Good [30]
Cork				Average [30]	Average [30]
Sheep-wool			30 [31]	Average [30]	Average [30]
Cotton-wool				Average [30]	Average [30]
Coconut fibers			230 [31]	Average [30]	Average [30]
Cellulose	30–45 [32] 30 [32] 30–60 [32]	0.041–0.050 [32] 0.041 [32] 0.050 [32]	133 [31]	Average [30]	Average [30]
Siliconated calcium					
Gypsum foam				Average [30]	Good [30]
Wood-wool				Poor [30]	Good [30]

4.2 Vacuum insulation panel

Vacuum insulation panels (VIP) are components whose performance is dependent on the absence or reduction of gaseous pressure inside an open-porous material, which would increase its thermal insulating potential. There are three major components: core material, gas barrier/facer foil and a getter/desiccant, as shown in Figure 2. Within a low gas permeability (small pores around 10–100 nm) width.

Figure 2 Vacuum insulation panel typical vacuum insulation panel structure showing the main components.



hin laminate film, the core material is enclosed. It is typically evacuated to 0.2–3 mbar of pressure, depending on thermal conductivity of core material (2–4 mW/(m K).Impermeable gas barrier is enclosed with the open porous core materials and vacuum insulation panel thermal insulating capacity is higher than conventional insulating materials which are up to 10 times. Application of the panels where space is at a premium (higher insulating value is desired) will be useful by vacuum insulation panel property. Nevertheless, the vacuum insulation panel proper application can be difficult since it is fragile and high cost. In addition, the thermal properties of vacuum insulation panel might decrease through time. Irreversible pressure will be increased in the vacuum insulation panel, if the laminate is not perfectly gas-tight and potentially make gas molecules to diffuse through the envelope. The type of laminate, the core material, and the surrounding climate will be decisive of the increment of pressure speed. Certain aspects of vacuum insulation panels, ranging from analy-tical models, thermal bridges and conductivity, air and moisture penetration, ageing and service life, quality control and integration of vacuum insulation panels in building construction have been studying by some authors. The structure of vacuum insulation panels inbuilding system have been studied in China which is shown in Figure 3,based on the described installation method, the material layers can be showed by the sectional view of an insulated wall system.

4.3 Gas filled panel

Gas filled panels (GFPs) are the new advanced applications of ambienttemperature thermal insulation. GFPs are made of infrared reflecting (low emissivity) and multilayer baffles enveloped by a sealed barrier and filled up with air at atmospheric pressure or a low conductivity gas Figure 4 shows an inside view of GFP on the barrier foil with abstractor. Low thermal conductivity gases, or air is employed for gas-fill. The barrier is sealed hermetically for maintaining the gas-fill, while the baffles are necessary to suppress convection and radiation. However, itis found that the thermal conductivities of prototype GFPs are slightly higher than current traditional insulation. Therefore, the application ofGFPs is still being argued. In spite of that, there are still numerous potentials of low conductivity gases to be applied for developing high-performance insulation technologies such as a noble gases (with the inertargon, krypton, and Xenon)

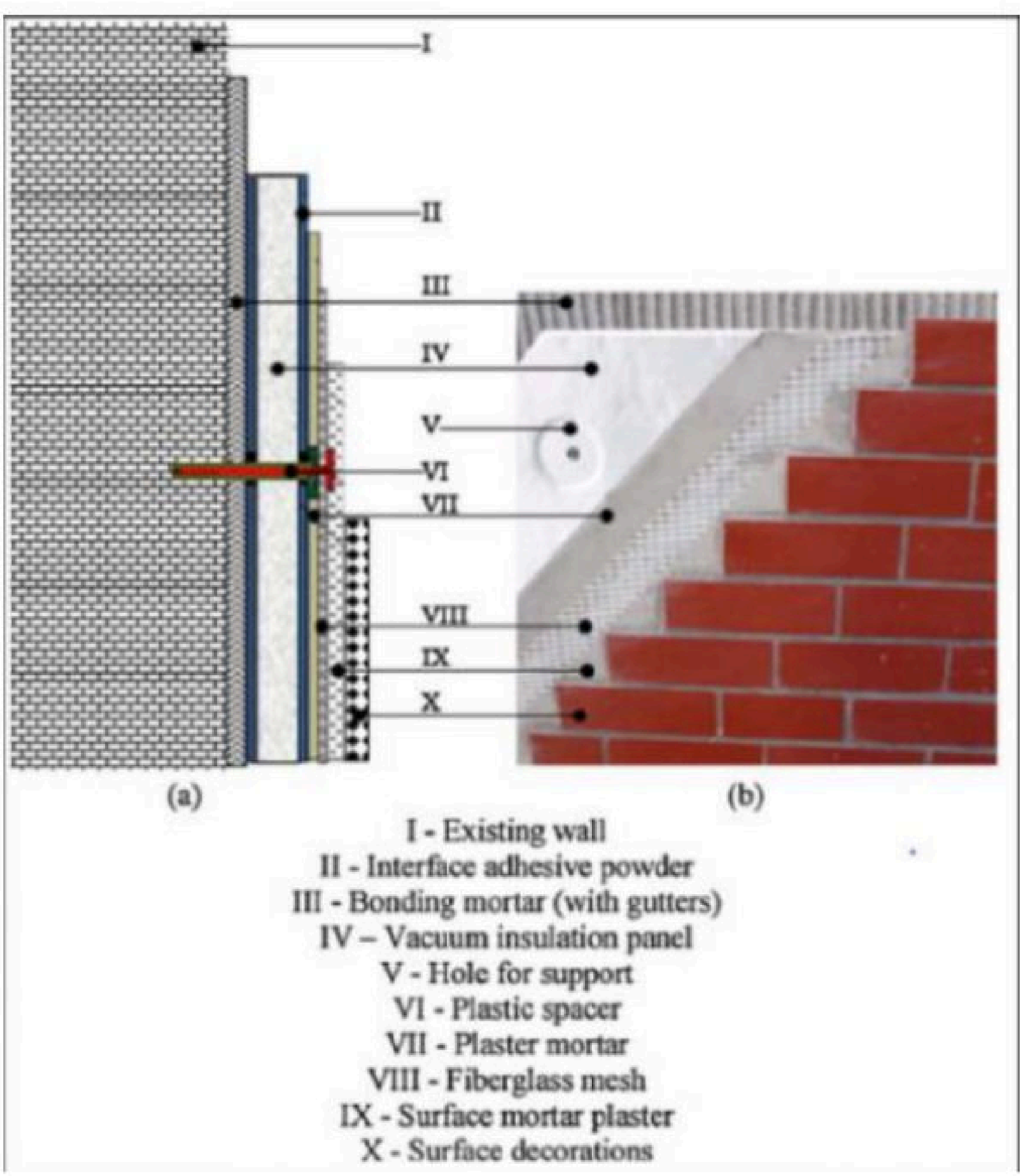
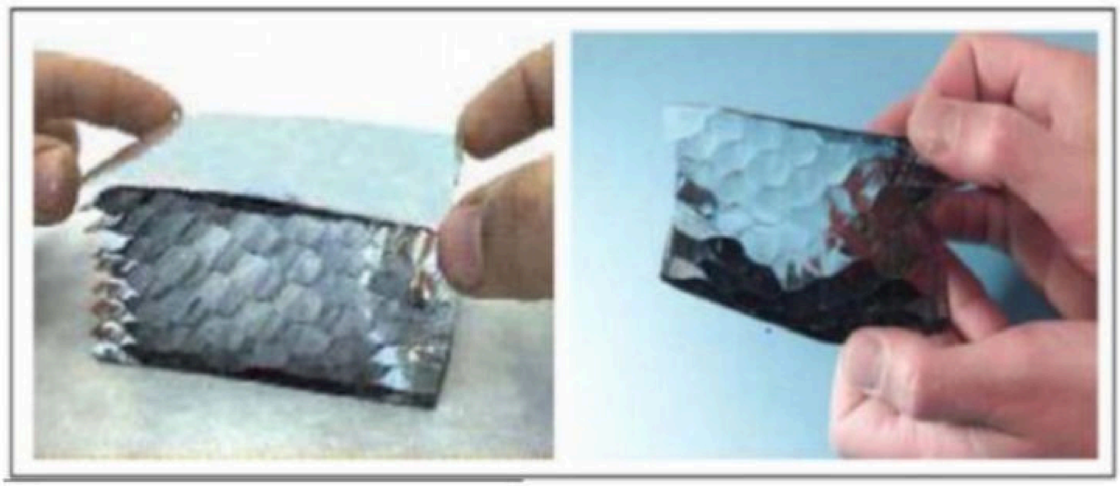


Figure 3 Assembly of vacuum insulation system: (a) cross-section and (b) pictorial view of insulated wall.

Figure 4 An inside view of GFP on the barrier foil with baffle structure.



5 Application of building insulation

In general practice, it is a strategic approach to insulate a building from main components, including walls, doors and windows, where heat transfer predominantly takes place. Thermal insulation helps in preserving energy efficiency, which depends on the air temperature gradient (the difference between inside and outside of building),geographical location, climatic condition and heating space type .This paper briefly covers the approachable application of building insulation materials on wall, roof and ceiling, windows and floor.

5.1 Insulation on wall

Conservatively woods or bricks construct walls, and from thermal perspective they have a desirably lower heat conductivity than glass and metal. Since walls occupy the biggest account of a building, however, employment of thermal insulation directly affects majorly the overall building heat gain/loss. The performance of insulation materials on transient heat flow of a building's wall can be affected by the placement of insulation material. In order to achieve best performance, the insulating material should be installed close to the location of the heat inflow or outflow. However, the insulation is normally installed inside or between the wall cavities for practicality.

5.2 Insulation on roof and ceiling

A direct beam of sunlight during the day causes the roof to gain significant amount of radiative heat from sun. Roofs can represent up to 32% of the horizontal surface of built-up areas and contribute great of heat gain in buildings. Reflective insulation is normally used on the roof as radiant barrier; this type of insulation should have enough air gaps to effectively reduce heat transfer through conduction and convection. In contrary to thermal mass insulation that insulates through absorption, reflective insulation reflects the thermal radiation back to its source. In this application, they are much more operative in hot climates than cold climates. In cold climates, the insulation is normally limited to the ceiling. Snow melt patterns on rooftop are a good indicator of energy efficiency in buildings. It is a sign that heat is losing through the attic and is being wasted.

5.3 Insulation on windows

In a well-insulated house windows are the second important heat sources. Due to the nature of the windows, they are usually transparent, which means the light can pass through them and can carry the heat inside the conditioned space; they are strongly affected by solar radiation and the airflow surrounding. Heat loss/gain through the windows can be controlled by bulk insulation and minimizing glazing. There are numbers of relatively new insulation technologies introduced and incorporated on windows, but two of the most prominent technologies are gas filling and low-Emittance (low-E) coating. Low-E coatings are metal or metallic oxide layers that are virtually invisible and are deposited on the surface of window glass to suppress radiative heat flow by reflection. Meanwhile, gas filling, with lower thermal conductivity than air, occupies the spaces between window panels for insulation purpose. The most popular inert gas used for gas fill insulated glass is argon.

5.4 Insulation on floor

Floors, such as those over unheated crawl spaces and concrete slab, are also advised to be properly insulated. The insulation is being applied around the perimeter of the slab of the footings. However, the insulation for concrete slabs of basement floors is considered as having limited value because the heat transfer into the ground at the lower depth of basement floors is comparatively low. This low heat transfer is resulted from relatively small variation of temperature between the ground under the floor and the air above the floor.Table 3 Recent studies based on application of building insulation shows the study conducted by several researchers, the isolation in certain parts of the building. Insulation of buildings is done by using variety of building insulation materials is accompanied by its thermal conductivity.

Table 3 Recent studies based on application of building insulation

Building component	Material	Thermal conductivity (λ) (W/m K)	Reference
Floor	Fiberglass (sand & recycled glass)	0.04–0.033	[20,24] [29] [23]
	Rockwool (natural rocks)	0.037	[20,24] [29] [23]
	Polyethylene	0.041	[20,24] [29] [23]
	Cellulose (ground-up waste paper)	0.054–0.046	[29] [13,24]
	Perlite (natural glassy volcanic rock)	0.06–0.04	[29] [13,24]
	Vermiculite	0.068–0.063	[29] [13,24]
	Expanded Polystyrene (closed cell foam)	0.038–0.037	[29] [20]
	Extruded Polystyrene (closed cell foam)	0.032–0.030	[29] [20]
Wall	Fiberglass (sand & recycled glass)	0.04–0.033	[20,24] [23,29,119]
	Rockwool (natural rocks)	0.037	[20,24] [29] [23]
	Polyethylene	0.041	[20,24] [29] [23]
	Expanded Polystyrene (closed cell foam)	0.038–0.037	[29] [20]
	Extruded Polystyrene (closed cell foam)	0.032–0.030	[29] [20,120]
	Cellulose (ground-up waste paper)	0.054–0.046	[29] [13,24]
Ceiling	(open cell structure)	0.038–0.030	[20,24] [29] [23]
	Rockwool (open cell structure)	0.040	[20,24] [29] [23]
	Cellulose (ground-up waste paper)	0.054–0.046	[20,24] [29] [23]
	Perlite (natural glassy volcanic rock)	0.06–0.04	[20,24] [29] [23]
	Vermiculite	0.068–0.063	[20,24] [29] [23]
Roof	Fiberglass (sand & recycled glass)	0.04–0.033	[20,24] [29] [23]
	Rockwool (natural rocks)	0.037	[20,24] [29] [23]
	Polyethylene	0.041	[20,24] [29] [23]
	Expanded Polystyrene (closed cell foam)	0.038–0.037	[29] [20]
	Extruded Polystyrene (closed cell foam)	0.032–0.030	[29] [20,120]
	Cellulose (ground-up waste paper)	0.054–0.046	[29] [13,24,120]

One of the easy and effective ways of energy conservation technologies available today is through building insulation. It offers a number of applications in residential, commercial and industrial sectors. The main objective of installing insulation material in the building is to reduce energy consumption for heating or cooling by increasing the thermal resistance of the building envelope. By increasing the insulation thickness the thermal conductivity will be reduced, while the insulation cost will be increased until it exceeds the savings, which this additional thickness will not bring any economic benefit. Therefore, the optimum insulation thickness exists where the savings start to drop by increasing the thickness of insulation. Many substances can be used as insulation material such as fiberglass, mineral wool, foam and other materials are also utilized in producing the insulations. Building insulation is also by means an energy saving method as well as reducing negative environmental impact of the greenhouse gas the buildings emit. This review article fits as the fundamental reference for developers in building insulation application and for policy makers to implement insulation as one of the energy conservation strategy.

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