International Journal of Mechanical and Production Engineering, ISSN(p): 2320-2092, ISSN(e): 2321-2071
Volume- 8, Issue-5, May.-2020, http://iraj.in

A REVIEW OF LOW ENERGY THERMAL INSULATION MATERIALS FOR BUILDING APPLICATIONS

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Abstract - In response to the need for reducing energy demand for heating and cooling in buildings, 'fabric first' approach is suggested and prescribed by building regulations and voluntary standards worldwide. The 'fabric first' approach focuses on reducing the U-value of building envelope by applying efficient and adequate thermal insulation materials. As operational energy demand of buildings is gradually reducing, the embodied energy of buildings is becoming a major contributor to carbon emission compared to operational energy. As such it is pertinent to specify building materials with low embodied energy and lessened environmental impact. This paper reviews thermal insulation materials with low embodied energy and lessened environmental impact and compares them with conventional but high-impact insulation materials.

Keywords - Embodied Energy, Operational Energy, U-Value, Thermal Insulation, Sustainable Materials.

I. INTRODUCTION

Due to the process of 'Global warming', earth's temperature has increased by 1°C above the preindustrial level in 2017[1]. The IPCC predicts that more than1.5°C increase of temperature above the preindustrial level will result in irreversible climatic changes leading to environmental catastrophe. The widely acknowledged scientific consensus is that, carbon emission due to anthropogenic activities is the main cause of global warming. In many countries, construction sector contributes to more than 40% of the total carbon emissions[2]. In buildings, the highest contributor to carbon emissions is space heating and cooling using mechanical devices. To reduce the load of space heating and cooling, the 'fabric first' approach is prioritised focusing on insulation loft spaces, roofs and building envelopes to achieve lower U-value or thermal transfer coefficient. Gradually, the operational carbon emissions are reducing. However, as much as 30% of buildings' life cycle carbon emissions is committed before a building starts operating due to the embodied energy of the building materials. Therefore, it will be increasingly important to reduce embodied carbon of building materials. Additionally, due to the advert effect of plastics on environment and depletion of mineral resource, it is also pertinent to use materials that are sourced from renewable and sustainable sources. This paper reviews several thermal insulation materials and compares them in terms of their embodied energy and sustainability.

II. TYPES OF INSULATIONS

Worldwide, the number of thermal insulation materials for building applications exceeds forty. Thermal insulation materials can be divided into two major groups Based on the raw materials used, Organic (carbon based) and inorganic (lacking carbon-hydrogen bonds, mineral) thermal insulation materials. Organic and inorganic insulations can be subdivided into natural and synthetic insulations based on the sourcing of raw materials and processing. Table I presents the classifications of the thermal insulation materials on the above basis.

Inorganic (Mineral)		Organic (Carbon based)	
Synthetic	Natural	Synthetic	Natural
Aerogel	Expanded clay	Expanded Polystyrene	Cellulose fibres
Calcium silicate foam	Expanded mica	Extruded Polystyrene	Cotton fibre
Cellular glass	Expanded perlite	Melamine foam	Flax fibre
Ceramic fibres, ceramic foam	Expanded vermiculite	Phenolic foam	Hemp fibre
Foamed glass	Insulating clay bricks	Polyester fibres	Hemp-lime (Organic and inorganic)
Glass Wool	Pumice	Polyethylene foam	Insulation cork board
Gypsum foam		Polyurethane in situ foam	Sheep's wool
Pyrogenic silicic acid		Polyurethane rigid foam	Strawbales
Rock wool/Slag wool		Urea formaldehyde resin in situ foam	Wood fibres
			Wood Wool

TABLE I: Insulation classification and types[3]

Additionally, advanced insulation materials are also available in some countries. These advances insulation materials include vacuum insulation panels, switchable thermal insulations, transparent insulation materials etc. However, in the current paper, only following insulation materials will be discussed: mineral wool insulation, EPS insulation, hemp insulation and wood fibre insulation as they broadly represent three major sources of raw materials, e.g., mineral, petroleum and bio-based.

III. THERMAL INSULATION PROPERTIES

In this section some selected organic and inorganic thermal insulation materials are presented and characterised in terms of their key hygrothermal properties such as thermal conductivity, vapour diffusion resistance factor and embodied energy. The insulation materials can be thus compared in terms of carbon emissions, efficiency and sustainability characteristics.

A. Mineral Wool Insulation

Mineral wool insulation is one of the largest insulation industries in Europe. The European market share of mineral wool insulation materials is about 22%. Both rock wool and slag wool insulations are included within the broader definition of Mineral Wool insulation (Fig.1). About 80% of the mineral wool products are 'rock wool' in the European market which is opposite in North America.

1) Constituents and Manufacturing: The key ingredient of rock wool insulation are natural rocks such as basalt or diabase. Slag wool insulation materials are manufactured from iron ore or blast furnace slugs.To manufacture mineral wool insulation, rocks or blast furnace slag are melted and spun into fibres by pouring the molten material on spinning wheels and mixing the fibres with a binding and a dedusting agent.

2) Form, dimensions and application: Mineral wool slabs or batts are installed in masonry cavity walls, for friction fits between studs, joists and rafters, timber frame walls and pitched roofs, partition walls, party separating walls. The slabs are available mainly in the dimensions of 1200X 600 mm, 1200 X 455 mm. The thickness can vary between 50 mm to 160 mm.

Fig. 1. Mineral wool insulation slabs.

Mineral wool rolls can be installed on loft spaces and over ceiling tiles in suspended ceilings. The rolls are available in various dimensions such as 4800X400 mm, 4800X600 mm, 3650X400 mm, 3650 X 600 mm. The thickness can vary between 100 to 150 mm.

Mechanically granulated spun mineral wool insulation treated with water repellent agent can also be blown on lofts or masonry cavities. Typically, the installed density is 18-40 kg/m^3. The properties of mineral wool insulation is presented in Table II.

Property	Value
Thermal conductivity (W/m.K)	0.035-0.047 W/m.K
Specific Heat capacity (J/Kg.K)	850 J/Kg°C
Density (Kg/m^3)	21-250 kg/m^3
Porosity	95%
Compressive strength (kPa)	
Reaction to fire (EN 13501-1)	A1
Moisture buffer value, MBV (kg/m^2.%RH @8/16hrs)[4]	Negligible
Moisture adsorption at 98% relative humidity	Negligible
Water absorption, long-term (kg/m^2)	
Water absorption coefficient	
Vapour diffusion resistance factor μ	1-2

TABLE II: Mineral wool insulation properties[3]

3) Environmental attributes: Mineral wool insulation materials are manufactured from finite resources. The Global Warming Potential(GWP) and Ozone Depletion Potential (ODP) values are based on 1m^3 of insulation.

- Embodied energy: 16.6 MJ/kg (Bath)
- GWP 100 (cradle to gate): 44 kg CO2 eq
- ODP (cradle to gate): 3.6E-06 kg CFC-11 eq
- Recyclability: There is 25-50% recycled content by mass in mineral wool insulation BRE[5]
- Biodegradability: No
- Pollution: If formaldehyde is used as a binder, emissions are likely during the curing process. The residual formaldehyde remaining after the curing process may be emitted from the insulation.

4) Health Impact: The International Agency for Research on Cancer (IARC) classifies mineral wool insulation as 'B, possibly carcinogenic to humans'. Mineral wool insulation fibres are also skin and eye irritants. Exposure to mineral wool insulation may also result in upper respiratory tract infection.

B. Hemp Insulation

Hemp plants are very high yield crops. Hemp fibres are the bast fibres of the hemp plant. Hemp fibres are one of the strongest natural fibres in the world. Hemp fibre (Fig. 2) insulation is a non-woven fibre insulation made from the bast fibres of the hemp plant.

1) Constituents and Manufacturing: Bast fibres are renewable and biodegradable and they constitute the largest portion of hemp insulation, usually, more than 60%. Hemp fibres may be mixed with other fibres such as wood fibre, cotton fibre etc. To bind the fibres together, bicomponent polyester fibre and recycled adhesives are used.Alsofire retardants such as ammonium phosphate and anti-fungal agent are fixed in the metrics.

2) Form, dimensions and application: Hemp fibre slabs can be installed in roofs, attics/ loft spaces, walls (partitions), suspended ceilings, Internal wall partition, metal studded constructions or partitions, Internal dry-lining insulation in the refurbishment of masonry / solid constructions, Exterior insulation behind cladding and in suspended floors. The slabs are available in various dimensions such as 1200X570 mm, 1200X370 mm. The thickness can vary between 30 mm to 250 mm.

Fig. 2. Hemp insulation batts.

Hemp fibre rolls can be installed in attics/ loft spaces and suspended ceilings and floors. The rolls are available in various dimensions such as 1200/2400X570 mm, 1200/2400X370 mm. The thickness can vary between 30 mm to 250 mm

Property	Value
Thermal conductivity (W/m.K)	0.038-0.044 W/m.K
Specific Heat capacity (J/Kg.K)	1400-2300
Density (Kg/m^3)	25-60 kg/m^3
Porosity	95%
Compressive strength (kPa)	
Reaction to fire (EN 13501-1)	E or F
Moisture buffer value, MBV (g/m^2.%RH @8/16hrs)	1.7-2.7
Moisture adsorption at 98% relative humidity	17-60%
Water absorption, long-term (kg/m^2)	4.2
Water absorption coefficient (Kg/m$^2\sqrt{s}$)	0.031-0.041
Vapour diffusion resistance factor μ	1.5-2.7

TABLE III: Hemp insulation properties[3]

3) Environmental attributes: The GWP and ODP values are based on 1m^3 of insulation of a mean density of 42.5 kg/m3 (based on Andrew Norton).

- Embodied energy: 10 MJ/kg
- GWP 100 (cradle to gate): 14.7 KgCO2 eq.
- ODP (cradle to gate): No data
- Recyclability: Yes, Recycled Content: 37.5%.
- Biodegradability: Yes.
- Pollution: No known pollution.

4) Health impact: There is no known negative health impact of hemp insulation. Due to the insulations' high moisture buffer capacity, internal relative humidity can be stabilised which can contribute to a healthier environment.

C. Sheep Wool Insulation

Sheep wool insulation (Fig.3) is manufactured either from virgin wool or from pre-consumer wastes from other industries. Sheep wool insulation is hygroscopic but hydrophobic at the same time and that is why adsorbs moisture but repels liquid water.

1) Constituents and Manufacturing: Sheep wool insulation contains 75% to 90% pre consumer sheep wool waste from other industries. In some cases, virgin wools are directly used.Recycled adhesive binder (about 5%) or synthetic binder or natural latex milk are used as binding agents. To improve fire resistance and protect from moth infestation, borax (sodium salt) or urea derivatives or boric salts are added to the metrics.

The manufacturing sheep wool insulation involves a number of steps starting from the sheep firm or recycling centre. Initially, the wool is sorted based on colours and is packed into pressed bales. The bales are transferred to the scouring plant where the wool is blended according to the required specifications. Afterward, the wool is washed in a series of warm baths and finally chemical solution for fire and pest resistance are added to the wool in wet conditions. After drying, the wool is carded and mechanically bonded to achieve the target thickness.

2) Form, dimensions and application: Sheep wool insulation batts are available in various dimensions such as 400X1200 mm, 600 X 500mm, 600X 800 mm, 600X1200 mm. The thickness can vary from 40 to 200 mm. Sheep wool batts are applied in lofts, rafters, walls and inter-floors of timber frame structures and in stud walls separated from the external walls by a cavity.

Sheep wool insulation rolls are available in dimensions such as 380mmX6m, 380mmX9m, 570mmX6m, 570mmX9m. Typically the thickness varies from 50 mm to 150 mm. Sheep Wool Insulation rolls can be installed in internal & external walls, ceilings & rafters and floors.

Fig. 3. Sheep wool insulation.

The key properties of sheep wool insulation are presented in Table IV.

Property	Value
Thermal conductivity (W/m.K)	0.038-0.045
Specific Heat capacity (J/Kg.K)	960-1800
Density (Kg/m^3)	19-30 kg/m^3
Porosity	95%
Compressive strength (kPa)	
Reaction to fire (EN 13501-1)	B2- E
Moisture buffer value, MBV (g/m^2.%RH @8/16hrs)	1.8
Moisture adsorption at 98% relative humidity	30%
Water absorption, long-term (kg/m^2)	4.2
Water absorption coefficient (Kg/$m^2\sqrt{s}$)	0.031-0.041
Vapour diffusion resistance factor μ	1-5

TABLE IV: Sheep wool insulation properties[3]

3) Environmental attributes: The GWP and ODP values of sheep wool insulation are based on 1m3 of insulation of a mean density of 25 kg/m3 (based on Andrew Norton).

- Embodied energy: 6-20 MJ/kg
- GWP 100 (cradle to gate): Zero kgCO2 eq.
- ODP (cradle to gate): Zero Kg CFC 11 eq
- Recyclability: Sheep wool insulation can be reused if it is clean and in working condition. It can also be composted if boric salt is not used as an additive. If boric salt is used and if the sheep wool insulation is not in working condition, it has to be incinerated or disposed of for landfill.
- Biodegradability: Yes.
- Pollution:sulphur compounds can be released producing bad odour from the keratin of sheep wool if the insulation is burnt.

4) Health impacts: Due to its hygroscopic properties, sheep wool can maintain steady relative humidity in the interior by moisture buffering. Sheep wool can also adsorb VOCs like formaldehyde due to its high moisture and gas adsorption capacity.If exposed to, sheep wool dust may cause irritation to the airways and eyes.

D. EPS Insulation

Expanded Polystyrene or EPS insulation (Fig. 4) is the second largest insulation industry in Europe with 27% of the total market share.

1) Constituents and Manufacturing: EPS insulation is manufactured by adding pentane as a blowing agent and flame retardants to polystyrene beads, a thermoplastic polymer. When polystyrene beads are placed in a container and are exposed to high pressure steam, they expand by 30-60 times. The beads are injected in a moldand are fused into blocks after further expansion.

2) Form, dimensions and application: EPS insulation boards can be used for cavity wall insulation, exterior and interior insulation, perimeter insulation, underslab insulation and roof insulation. EPS boards are available at various dimensions such as 1200X450 mm, 1200X600 mm, 1200X1200 mm. Thickness can vary from 25 to 200 mm. EPS insulation is also used in Structural insulated panels (sips) and as cavity wall bead insulations.

Fig. 4. EPS insulation slabs.

The key properties of EPS insulation are presented in Table V.

Property	Value
Thermal conductivity (W/m.K)	0.030-0.045
Specific Heat capacity (J/Kg.K)	1500 J/Kg°C
Density (Kg/m^3)	10-35
Porosity	95%
Compressive strength (kPa)	
Reaction to fire (EN 13501-1)	E/F, ((‘B3’ in DIN4102)
Moisture buffer value, MBV (kg/m^2.%RH @8/16hrs)	Negligible
Moisture adsorption at 98% relative humidity	Negligible
Water absorption, long-term (kg/m^2), EN1609	<1
Water absorption coefficient	
Vapour diffusion resistance factor μ	20-100

TABLE V: EPS insulation properties[3]

3) Environmental attributes: The GWP and ODP values are based on 1m3 of naked insulation of a mean density of 40 kg/m^3.

- Embodied energy: 104.03 MJ/kg
- GWP 100 (cradle to installation): 82 kgCO2 eq.
- ODP (cradle to installation): 2.34E-06 Kg CFC 1 eq
- Recyclability: EPS is claimed to be 100% recyclable. However, there are not many facilities to recycle EPS insulation. Some forms of Styrofoam are banned in the city of New York as the city authority finds it impossible to recycle EPS economically.
- Biodegradability: No (It takes more than about 100 years to degrade)
- Pollution: Emissions from polystyrene factories can expose people to styrene.

4) Health impacts: Polystyrene is considered to be an endocrine disruptor, e.g., it contains chemical that can interfere with the activities of endogenous hormones which may cause disruption of biological signalling. Styrene is identified as a possible human carcinogen in 2002 by the International Agency for Research on Cancer and in 2014 by the US National Toxicological Program. Exposure to styrene can also cause eye, skin and upper respiratory tract irritations[6].

IV. DISCUSSION

The insulation materials discussed above have similar thermal conductivity. However, they are different in many other aspects. The biobased insulations have lower embodied energy than mineral wool and EPS insulation materials. Similar observation can be made in terms of their global warming potential. The biobased insulation materials (hemp and sheep wool) are biodegradable while the others are not. Therefore, it can be concluded that, while biobased insulations have similar thermal properties, they are better in terms of hygrothermal properties and sustainability.

V. CONCLUSION

In order to reduce carbon emissions from the construction sector, it is important to focus not only on operation energy but also on embodied energy. Thermal insulation materials are widely used for reducing heat transfer through the building envelope both for new and old buildings. As such, it is important to ensure that the insulation materials themselves not a source of carbon emission due to their manufacturing process and transport. Additionally, the insulation materials need to be sustainable meaning that they are manufactured from renewable resources and they are biodegradable at the end of their life. Considering all these issues, bio0based insulation materials seem to have better opportunities in contributing to reducing carbon emissions compared to mineral and petroleum-based insulations.

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