Quest Journals
Journal of Architecture and Civil Engineering
Volume 6 ~ Issue 9 (2021) pp: 59-65
www.questjournals.org

Research Paper

Thermal conductivity of insulating materials: An overview

Sooriyalakshmi. N[*1], Jane Helena. H [2]
[*1] *Department of Civil Engineering, Research Scholar, Anna University, Chennai,*
[2] *Department of Civil Engineering, Professor, Anna University, Chennai,*
Corresponding Author: N.Sooriyalakshmi

ABSTRACT
Air conditioning systems account for a bulk of total energy consumption in buildings. The major phenomenon behind thermal insulation is the conservation of energy. The study of the thermal performance of the building is essential to provide high comfort to the occupant as it helps to decrease the building's energy consumption effectively. This paper discusses the different types of thermal insulating materials, factors affecting thermal insulation, and methods to determine thermal conductivity. The materials discussed include natural materials like air, wood fibers, sheep wool, leaf, etc., recycled organic waste materials like bagasse, paper, corncob, coconut fiber, coconut shell, etc., and non-biodegradable materials such as plastics, synthetic rubber, etc. The thermal conductivity of these materials varies from 0 to 205W/mºK. The thermal conductivity can be measured by various methods such as the Guarded Hot plate method, Heat flow method, Hotwire method, Laser flash method, etc. These methods are also discussed.
KEYWORDS: *Fibers, Guarded Hot plate, Hotwire method, Insulation, Thermal conductivity, Waste*

Received 08 September, 2021; Revised: 21 September, 2021; Accepted 23 September, 2021 © The author(s) 2021. Published with open access at www.questjournals.org

I. INTRODUCTION

India is a developing country with emerging infrastructure throughout the nation. The construction industry consumes large energy and produces huge wastes [10]. A large amount of energy is being utilized by the building mainly due to the air conditioning system. The usage of air conditioning gives comfort with the enormous negative impact such as emission of Greenhouse gas and creates energy demand.

Nearly 2 billion tonnes of agriculture and industrial waste are generated worldwide every year with China positioned at the top as the producer of waste. In India, nearly 350 million tonnes of agricultural waste is generated apart from generating green fertilizer for farms [11]. According to Central Pollution Control Board, 5.6 million tonnes of plastic waste is collected annually and 26,000 tonnes of plastics daily out of which only 15,600 tonnes per day are being recycled others remain uncollected.[8].

Agriculture is the main occupation that produces a lump sum of waste. Due to the non-availability of proper infrastructure to handle a large quantity of agricultural waste is poorly disposed into the environment causing harmful effects leading to pollution problems [9]. To reduce CO_2 emissions and conserve energy, the provision of thermal insulators is one of the solutions.

The usage of plastic reaches a tremendous peak all over the world. The disadvantage of plastic is, it is difficult to decompose, tedious at disposal. Recycling can be done only on small scale. To achieve eco-friendliness in the disposal of plastic it can be used in the construction industry as insulation material [3].

In recent years insulation materials available in the market are mostly inorganic having high performance but also have environmental impacts during the production process. Usage of natural fiber gains importance amongst environment-conscious clients and designers [13]. Development of alternate insulating material with less impact on the environment is needed [9], therefore new insulating materials can be developed from recycled waste like

Plastics, leaves, twigs, coconut husk, coconut fiber, kenaf, bagasse, corn cob, rice straw, peanut shell, crumbed rubber, etc. [1,12,14]. The study of the thermal performance of the insulating materials helps to identify the green building materials to conserve energy by eliminating pollution to certain limits and provide a high comfort level.

II.THERMAL CONDUCTIVITY

Thermal conductivity is defined as the transmission of heat. To restrict the entry of heat from the exterior source, thermal insulation is provided. Materials with low thermal conductivity can act as a shield to prevent heat entry by conduction, convection, or radiation [1].

Thermal conductivity (K) $= \frac{\mathbf{Q.t}}{(\mathbf{T2 - T1}).\mathbf{A}}$

Where, Q - Total heat generated (W)
t - Thickness of panel (m)
A - Surface area of the panel (m^2)
T_2-T_1 - Difference in temperature in ^oC

2.1Factors affecting thermal insulation

The major factors affecting thermal insulation are

- Thermal conductivity
- Density
- Insulation thickness
- Moisture content
- Alkali treatment
- Particle size

Thermal conductivity is inversely proportional to thermal insulation. Thermal insulation is higher when thermal conductivity is reduced. Thermal conductivity varies by varying density, moisture content, and alkali treatment. The thickness of the panel is inversely proportional to the density of the material and the amount of heat transfer [10, 13].

2.2. Thermal Conductivity of Insulating Materials

The insulating materials are classified into two categories,

- **Natural materials**
- **Recycled waste materials**
  - **Biodegradable**
  - **Non-bio degradable**

i) Natural materials

Wood fiber is the natural insulating material that has been used since the twentieth century due to air pockets within its cellular structure. 50% of wood produced is converted into useful products and the remaining as wood waste. The wood waste may be in different forms as sawdust, chips, shavings, etc [19]. Wood waste is mainly composed of lingo cellulosic material which has low embodied energy and moisture-holding capacity which can be good thermal insulators [13]. The chemical composition comprises cellulose of 40-45% hemicelluloses of 20-30% and lignin of 20-32. The thermal conductivity of wood ranges from 0.048 to 0.055W/mK which depends on the density of wood and not on the type of wood [10,13]. Wood waste is recyclable and economical hence used in numerous applications such as fuel for cooking, in the construction industry as a core material for lightweight construction indoor and on the facade or layered boards, packaging material for thermal and sound insulation [10].

Tree leaves have a greater advantage of material longevity, maintain moisture level, prevent pest and rodent appearance hence can act as heat insulating material. The addition of 1-5% of quicklime with leaves decreases the thermal conductivity by 20%. The thermal conductivity of leaves is 0.0462W/mK. It can be used in walls and roofs to provide zero heat loss in buildings [9].

Sheep wool which is one of the worldwide available renewable resources can be used as thermal insulators that provide positive health effects. Major production of sheep wool is from Romania and at the national level production is from Jammu & Kashmir. Numerous air spaces in the fibers make them suitable for thermal insulation [12]. The thermal conductivity of sheep wool is 0.0314W/mK [7]. The advantage of sheep wool is that it is easy to use, has a low health impact, and is energy-efficient production. It has various applications in building material for manufacturing rigid boards used in walls and floors, in aviation, architecture, medical use, fashion, and protective cleaning [12].

ii) Recycled waste material

a) Biodegradable waste

Baggase is the residue from sugarcane after extracting the juice. India ranks second next to Brazil in sugarcane cultivation. The chemical composition includes cellulose of 40-46%, hemicelluloses of 24.5-29%, Lignin of 12.5-20%, and ash of 1.5-2.7%. Due to its low density and low thermal conductivity of

0.046W/mK, it can be used as a thermal insulator. The primary function of baggase is a cheaper source of electricity, feeder for cattle, and used in furniture making. In a building, it can be used as filler between cavity walls for raised flooring, partition walls, and sub-copings to maintain thermal inertia for the environment [21].

Coconut husk production is nearly a 4.5million tonnes per year in India. Properties of coconut husk are as follows: Tensile strength: 15-327MPa, Water absorptivity:80-90%, and it has excellent sound and thermal insulation with flame retardant properties, it is less toxic, low cost, tough and durable. Coconut husk has a thermal conductivity in the range of 0.054-0.143W/mK. [1, 2] .

Rice is the major food crop of India, cultivated nearly 114 million tonnes per year. The residues are rice husk and rice straw. Rice husk consists of cellulose 43.30%, hemicelluloses of 28.6%, and lignin of 22%. The husk is used as biofuel and as a ceiling board in Nigeria. Rice straw comprises 36% of cellulose, 24% of hemicelluloses, and 15.6% of lignin, whereas straw is generally used as a cattle livestock feeder. In construction, strawboard panels are an excellent thermal insulator [19].

Corn cob is maybe a natural, organic, renewable, and native raw building material. Corn cob is a lignocellulosic material that comprises 69.2% of cellulose, 28.2% of hemicellulose, and 8% of lignin [19]. The thermal conductivity of corn cob is 0.096W/mK. China is the leading producer of corncobs. In India ethanol is extracted from corncob [19] The corn cob particleboard has various applications in lightweight partition walls, ceiling coating, and interior doors[4].

Newspapers are composed of nearly 82% to 85% cellulose. Recycled old newspapers give a large amount of fiber [1]. Newspapers can act as a shield to reduce the rate of heat transfer and are also abundantly available[20]. The thermal conductivity of paper is nearly 0.230W/mK.

Groundnut shell is also a lignocellulosic material, produced at nearly 7.54 million tonnes annually. It comprises nearly 35.7% of cellulose, 18.7% of hemicellulose, 30.2%of lignin, and 5.9% ash. The thermal conductivity ranges from 0.153-0.140W/mK and it is suitable to act as a thermal insulator being eco-friendly and cost-effective. The use of groundnut shells ranges from packaging industries to the automotive sector and in the construction industry as panel reinforcement.[16,18].

Table 1: Chemical composition of agricultural waste [18]

Species	Cellulose (wt%)	Hemicellulose (wt%)	Lignin (wt%)	Ash (wt%)
Pine (softwood)	40-45	25-30	26-34	-
Maple (hardwood)	45-50	22-30	22-30	-
Banana	63-64	19	5	-
Coir	32-43	0.15-0.25	40-45	-
Sisal	63-64	12	10-14	-
Jute	61-71.5	12-20.4	11.8-13	2
Kenaf	31-39	21.5	15-19	-
Hemp	70.2-74.4	17.9-22.4	3.7-5.7	-
Bagasse	40-46	24.5-29	12.5-20	1.5-2.4
Groundnut shell	35.7	18.7	30.2	5.9
Rice husk	31.3	24.3	14.3	23.5
Pineapple	81	-	12.7	-

b) Nonbiodegradable waste

According to Central Pollution Control Board, 5.6 million tonnes of plastic waste is collected annually and 26,000 tonnes of plastics daily out of which only 15,600 tonnes per day are being recycled. The plastic waste consists of High-density polyethylene (HDPE), Low-density polyethylene(LDPE), Polypropylene(PP), and Polyethylene terephthalate (PET). The air-filled PET bottle lowers the thermal conductivity [5,6] of concrete and provides better thermal insulation. Thermal conductivity of HDPE is between 0.74-0.96W/mK, for LDPE it ranges between 0.72-0.86 W/mK, for PP 0.84-0.94W/mK and for PET it ranges between 0.95-1.02 W/mK[6]. Concrete with LDPE fibers is used in precast wall construction as the non-load-bearing walls to insulate heat transfer and reduce energy consumption inside the room. Rubber consists of polypropylene fiber which is suitable for insulation. When crumb rubber is mixed with gypsum the thermal conductivity is reduced [22]. Rubber mixed with concrete gives increased durability to concrete hence reduces the cost of construction, preventing the accumulation of raw materials causing pollution to the environment [22].

Table 2: Thermal conductivity of various core insulating materials [1, 9,10,13]

Material	Thermal Conductivity(K) W/mºK
Air	0.026
Leaves	0.0462
Kenaf	0.0208
Wool	0.03-0.04
Silica aerogel	0.026
Recycledcellulose aerogel	0.032
Aspen aerogel	0.021
Nagpur Orange	0.586-0.7473 W/mºC
Pineapple leaves	0.035
Plastic	0.400
Bagasse	0.046
Textile	0.230
Oil palm leaves	0.127
Twigs	0.130
Paper	0.230
Corn cob	0.096
Rubber	0.130
Coconut fiber	0.140
Coconut shell	0.143
Granite	1.700
Wood	0.130
Aluminum	205
Iron	80
Glass	1.05
Concrete	0.7
Aramid Honeycomb	0.06
Graphite	135

III. METHODS TO MEASURE THERMAL CONDUCTIVITY

There are different methods to measure thermal conductivity. In general, it can be classified as a steady-state method and transient or unsteady-state method.

In a **steady-state method**, a steady-state condition is attained when the temperature at each point of the specimen is constant and the temperature does not change with time. A disadvantage is that it generally takes a long time to reach the required equilibrium. This method involves expensive apparatus since a well-designed experimental installation system is usually needed. Nevertheless, it is the primary and most accurate measurement method [15,17].

In the **Transient method**, the measurement is taken during the healing process. Thermal conductivity is measured using sensors and probes. The measurement can be made quickly compared to the steady-state method. The transient method is more suitable for materials with heterogeneous properties and high moisture content
[15,17].

3.1 Steady-state methods

i)Guarded hot plate method (GHP*)*

The guarded hot plate method is otherwise called as Poensgen apparatus. It is the most effective method for measuring the thermal conductivity of insulating material in common. In the guarded hot plate method the heat flows from hot plate to cold plate steadily. The advantage of the GHP method is that it is the ideal apparatus for researchers and scientists in the field of insulation testing and it is considered an absolute measurement method. The accuracy of this method is uncertain that turns to be the disadvantage of this method. The details of this method are provided by the American Society for Testing Materials (ASTM)[15].

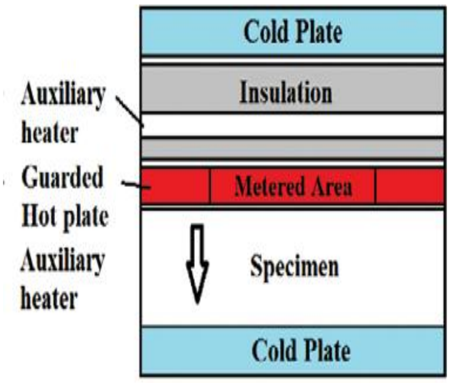

Fig 1: Guarded hot plate method [12]

ii) Heat flow meter

The heat flow meter is more accurate and less time-consuming compared to the Guarded Hot plate method. This method shows the best result for measuring the thermal conductivity of low conductivity materials. The highest temperature limit is 200ºC but for a practical application, it can be limited to 100ºC. The apparatus design of the heat flow meter is similar to that of the guarded plate method with a single specimen. The heat flow method is a relative method [15]

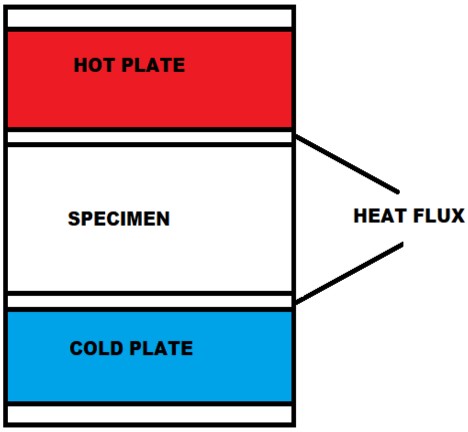

Fig2: Schematic diagram of heat flow meter

Insulating materials, polymers, glass, ceramic and other materials with thermal conductivity not greater than 5W/mK can be detected using a heat flow meter [15]

3.2 Transient or unsteady-state method

i) Hotwire method

The hot wire method is based on the increase of temperature at a distance from the heat source. Hotwire methods can be used to determine the thermal conductivity of liquids. In the hot- wire method, the specimen preparation is simplified by the utilization of a heat source, except within the case of solids. When solids are being tested, the wire is situated between two equally sized homogeneous specimens as shown in figure 3

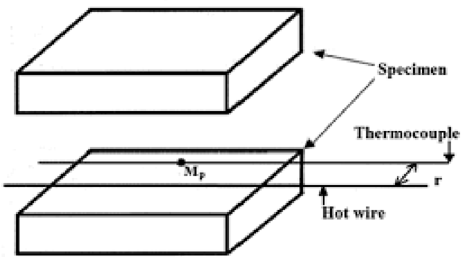

Fig3: Parallel Hot Wire Method [15]

*Corresponding Author: N.Sooriyalakshmi

The transient hot-wire method consists of two systems, a wired system, and a probe system. In the hot wire method, the wire may be placed in parallel or across. The source of heat is by supplying stabilized electrical power supply to get the output. In parallel hot wire technique temperature sensor and heater are separated but in cross-wire technique, both sensors and heater are connected by a thermocouple. The parallel wire technique is used to measure thermal conductivity within 20W/mK whereas the cross wire technique is used to measure thermal conductivity below 2W/mK. The thermal conductivity of biological materials, insulations, rocks, ceramics, foods, soils, and glass over a wide range of temperatures is measured using the hot wire/probe method. Hotwire method has limitations while measuring the thermal conductivity of solids [15].

ii) Laser flash method

The laser flash method is used to determine the thermal conductivity of solids. The temperature range of -100ºC to 3000ºC can be measured. In this method, radiation is sent to the front side of the specimen, and the temperature change on the backside is measured. The specimen is heated with a short laser pulse of 1-millisecond width on the front side of the specimen. The temperature increase at its rear side is measured and determined. The laser flash method has the advantage of involving neither temperature nor heat-flow measurements for the determination of a thermal property. The measurement of the thermal diffusivity is calculated based on the relative temperature change as a function of time only.[15,23]

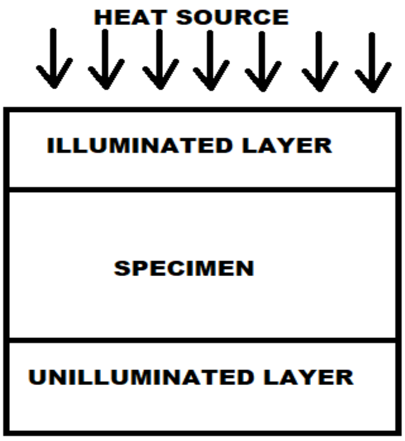

Fig4: Principle of Laser flash method

3.3 Field testing

Infrared thermometer

An infrared thermometer can be used to determine the surface temperature of an object. An infrared beam bouncing off the surface cannot measure the interior temperature. Every object emits some amount of energy in the form of heat. An infrared thermometer makes use of the difference between infrared rays coming off the object and the surrounding environment to determine the temperature of the object. It works by focusing the light coming from the object in the form of infrared waves and funneling that light into the detector. This detector is also known as thermopile in which the infrared radiation is turned to heat which is again converted to electricity and then measured. The more electricity is sent to the detector, the higher temperature is observed [1].

Fig5: Infrared thermometer [1]

IV. CONCLUSIONS

Excessive usage of natural resources leads to a decline of the resources, so converting the waste (agro waste, Industrial waste) by-product effectively into value-added products is of importance. The waste material with a property similar to wood can be used as thermal insulators. The more porous materials, lightweight, and the insulation layer with voids enhance the thermal performance of the panels. Natural insulation materials have better environmental aspects and show better efficiency compared to conventional insulation materials. Materials with glazing surfaces have better thermal insulation due to less absorption of thermal radiation. Low thermal conductivity improves the thermal conditioning of the building. The advantage of using a by-product is the ease of use, low health impact, and energy-efficient production. The usage of recycled waste is cost-effective and less time-consuming. All the methods to measure thermal conductivity have pros and cons, a suitable and effective method, low cost, and less time-consuming have to be selected.

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