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Effect of cellulose fibre based insulation on thermal performance of buildings

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ABSTRACT

Cellulose fibre based insulation can be employed to maintain comfortable indoor conditions inside buildings and to improve energy efficiency. The huge energy consumption for space cooling can be decreased by applying cellulose fibre as thermal insulation in the buildings because of its low thermal conductivity. Cellulose fibre insulation is made from recycled paper fibres and inorganic additives are used to prevent mould growth and increase fire resistance. Here an effort has been made to examine the suitability of cellulose fibre as an insulation for buildings under static, dynamic heat transfer conditions, embodied energy and environmental pollution aspects are also examined. Cellulose fibre insulation has lower value of embodied energy and environmental impact as compared to other insulation materials. Cellulose fibre has lower embodied energy than the conventional and unconventional insulation materials. Cellulose fibre can be utilized in the buildings for maintaining a steady humidity value in the indoor air. Cellulose fibre board has the mean thermal conductivity equivalent to materials like cork, polyurethane, recycled glass, recycled cotton and glass wool. The cellulose fibre board has incredibly low mean thermal diffusivity than other materials like cork, polyurethane, recycled glass, recycled cotton and glass wool. Consequently cellulose fibre has similar thermal performance under static heat transfer conditions to the best insulation materials and the thermal performance of cellulose fibre for insulating buildings under dynamic heat transfer conditions will be much better than other insulation materials. Cellulose fibre is also environment friendly, renewable, recyclable and has lower embodied energy.

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1. Introduction

Buildings consume a major share of the total energy expenditure in the World. Around 30–40% of total energy consumption in the world is in the buildings and construction sector [1]. Building sector alone causes around 33% of the total greenhouse gas emission in the world [2]. The greenhouse effect from building sector will increase further due to rise in energy consumption in the near future [2–4]. Space heating and cooling consume a large portion of the energy expenditure in the buildings [5]. This large amount of energy consumption for space cooling can be reduced by using thermal insulation in the buildings. Insulating building envelope can make it energy efficient and can maintain comfortable indoor conditions as around half of the heat gain is through building envelope [2]. Natural insulation materials like cellulose fibre should be utilized for insulation purpose considering their low environmental impact, low embodied energy and similar insulation properties to synthetic materials [6–7]. Embodied energy is spent in each stage right from the production of material, delivery, construction and demolition [8]. Natural insulation materials like cellulose fibre are sustainable, renewable and environment friendly during life cycle and production and are much better as compared to non-renewable synthetic materials which creates lot of pollution during production. New cost effective, sustainable and environment friendly materials are beings tried in buildings to reduce the energy consumption and environmental impact [1]. Cellulose fibre is one such option for use as an insulation in the buildings. Thermal insulation material can be prepared from sustainable cellulose fibre material using recycled paper [9]. The cellulose fibre can be used for insulation in loose fill form or in the form of a fibre board. Gravity compacted cellulose fibres in loose state can be used as an insulation as its thermal conductivity in loose state is comparable with conventional materials [10]. Fibre boards which are friendly to the environment can be made from cellulose using biodegradable, renewable and recyclable materials [11]. The

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thermal conductivity of cellulose fibre is low and has a value around 0.04 W/mK [1]. This is comparable with conventional and unconventional insulation materials being used at present. The peak relative humidity can be lowered by 10% using hygroscopic cellulose insulations and the advantage of hygroscopic cellulose insulation increases under hot and humid outdoor conditions [12]. The heat interaction in buildings with outside is dynamic in nature and depends on the thermal diffusivity of the insulation material being utilized. A lot of work has been carried out on the natural and synthetic insulation materials and their suitability for use in buildings and not much work is done on the suitability of cellulose fibre for use in buildings under dynamic heat transfer conditions.

Keeping the above literature in mind the suitability of cellulose fibre as a thermal insulation for buildings in the form of fibre board is to be investigated in the present work under the static and dynamic heat transfer conditions, embodied energy and environmental pollution aspects are also to be scrutinized.

2. Cellulose fibre and fibre board

The various aspects of cellulose fibre and cellulose fibre boards are discussed in the following sections.

2.1. Cellulose fibre

Cellulose fibre is one of the easily available bio-based insulation materials with its properties available in the literature [13]. Cellulose fibre insulation is prepared from recycled paper fibres [1]. Inorganic additives are added during preparation of cellulose fibre to inhibit mould growth and withstand fire [1,14]. The use of cellulose has increased recently due to low coefficient of thermal expansion, high surface area, flexibility and biodegradability [15]. Cellulose fibre has high durability, low density and high strength apart from being a renewable material [16]. Cellulose fibre has its properties suitable to be used as an insulating material and is eco-friendly, therefore thermal insulating materials can be produced from cellulose fibre [17].

2.2. Cellulose fibre boards

Fibre boards can be made from cellulose using biodegradable, renewable and recyclable materials. These fibre boards are friendlier to the environment and the flexural properties of boards prepared cellulose fibre can be better than wood fibre plastics and natural fibre reinforced plastics [11]. The environmental impact and carbon footprint of these boards prepared from cellulose fibre are expected to be lower as compared to other materials [11]. These boards are green substitute to the conventional materials used for buildings [11].

3. Lower environmental impact and embodied energy

Natural insulation materials like cellulose fibre have low environment impact, low embodied energy and have similar insulation properties to synthetic materials [6,7]. Greenhouse gas emission and embodied energy of the buildings can be reduced up to 15% by replacing the rock wool insulation material by cellulose fibre [18]. Cellulose fibre is derived from biobased natural materials. The biobased materials are natural alternative to non-biobased materials to mitigate their environmental effects [19]. The biobased materials are carbon neutral due to the fact that the carbon emitted at the end of life is considered equal to the carbon sequestration at the forest [20]. Utilization of more natural biobased materials like cellulose fibre in buildings can lower the life cycle environmental impact of buildings taking into account the biogenic carbon dioxide emission and sequestration [21].

Embodied energy is minimum for sustainable insulation materials as compared to other insulation materials [2]. The embodied energy for cellulose fibre lies amongst lowest as compared to other natural and synthetic insulation materials [1,6]. Cellulose fibre has lower embodied energy (0.94–3.3 MJ/kg) as compared to conventional insulation materials like mineral wool or rock wool (16.6–16.8 MJ/kg) and unconventional materials [10].

4. Indoor humidity control

The indoor air humidity and comfort is affected appreciably by the transport of moisture between hygroscopic insulation and the indoor air [12]. The indoor moisture buffering effect can be enhanced by employing high density cellulose fibre insulation on the inner side of the buildings [12]. Cellulose fibre is a hygroscopic material and act as a buffer for humidity and maintains a constant moisture level in the indoor air [22]. The hygroscopic properties of cellulose fibre as thermal insulation can be used to smoothen out the peak levels of indoor humidity under dynamics conditions and thereby improving the thermal comfort inside a building [12].

5. Thermal performance

The thermal performance of an insulation can be defined in terms of properties like thermal conductivity and thermal diffusivity. The thermal conductivity is a measure of thermal performance of an insulation under static heat transfer conditions. The thermal diffusivity is a measure of thermal performance of an insulation under dynamic heat transfer conditions like heat transfer in building during the day and night. Cellulose fibre insulation has good thermal properties and is environment friendly and has similar thermal properties to that of conventional thermal insulation materials [1]. The mean thermal conductivity and mean thermal diffusivity of the various insulation materials were computed from the data available in the literature [2,11,23]. The worked out mean thermal conductivity and mean thermal diffusivity are presented in the coming sub-sections.

5.1. Mean thermal conductivity

The mean thermal conductivity figured out for different insulation materials considered for the analysis is presented in Table 1 and Fig. 1. The mean thermal conductivity of the cellulose fibre board is comparable with materials like cork, polyurethane, recycled glass, recycled cotton and glass wool. It has slightly higher thermal conductivity than the polyurethane insulation. The thermal conductivity of cellulose fibre is almost same as that of the materials like cork and glass wool. The cellulose fibre has slightly lower thermal conductivity as compared to that of the materials

Table 1
Mean thermal conductivity and thermal diffusivity of various Insulations.

S. No.	Insulation	Thermal Conductivity (W/mK)	Thermal Diffusivity (x10^{-6} m^2/s)
1	Cellulose Board	0.039	0.046
2	Cork	0.040	0.227
3	Polyurethane	0.029	0.247
4	Recycled Glass	0.044	0.338
5	Recycled Cotton	0.042	0.729
6	Glass Wool	0.040	0.808

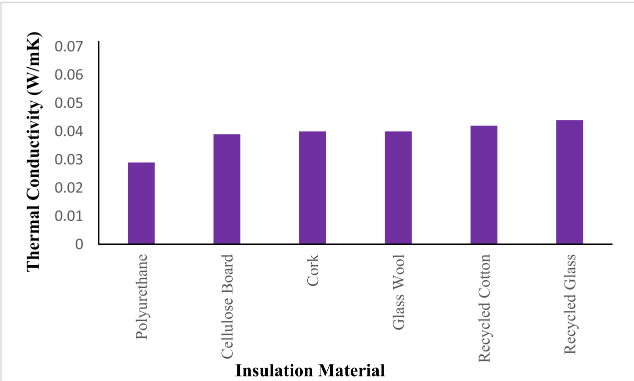

Fig. 1. Mean thermal conductivity of various insulation materials.

like recycled cotton and recycled glass. Therefore the thermal conductivity of the cellulose fibre is similar to other insulation materials considered in the study. The mean thermal conductivity of the cellulose fibre is 0.039 W/mK as compared to lowest value of thermal conductivity of 0.029 for polyurethane and maximum value of 0.044 for the recycled glass. So the thermal performance of cellulose fibre under static heat transfer is comparable with the best insulation materials being used at present. Using the cellulose fibre as insulation material under static heat transfer conditions is beneficial as compared to other materials because it is a renewable, recyclable, environment friendly and has lower embodied energy.

5.2. Mean thermal diffusivity

The mean thermal diffusivity calculated for various insulation materials considered for the investigation is presented in Table 1 and Fig. 2. The mean thermal diffusivity of the cellulose fibre board is far lesser than other materials like cork, polyurethane, recycled glass, recycled cotton and glass wool. The mean thermal diffusivity of the cellulose fibre is 0.046×10^{-6} m^2/s as compared to next lowest value of thermal diffusivity for cork 0.227×10^{-6} m^2/s and maximum value is 0.808×10^{-6} m^2/s for the glass wool. The mean thermal diffusivity of the cellulose material is about 5 times lesser than the next lower value for cork and around 18 times the value for glass wool. Thus the thermal performance of cellulose fibre under dynamic heat transfer conditions like insulating the buildings is much better than other insulation materials being utilized currently. Using the cellulose fibre as insulation material under dynamic heat transfer conditions is further advantageous as compared to other materials because it is a renewable, recyclable, environment friendly and has lower embodied energy as discussed earlier.

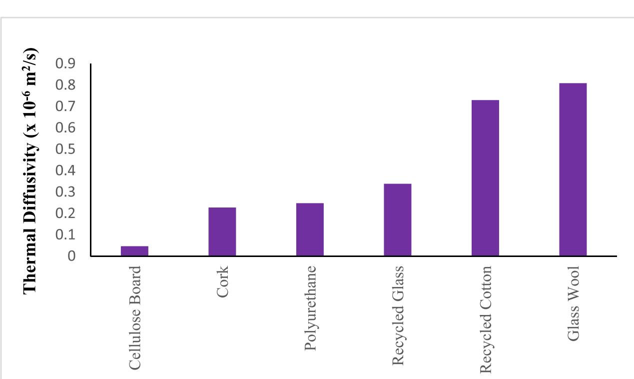

Fig. 2. Mean thermal diffusivity of various insulation materials.

6. Conclusions

In the present work the effect of the cellulose fibre as an insulation for buildings was evaluated along with its impact on the environment and embodied energy. Cellulose fibre insulation has low embodied energy and low environment impact as compared to synthetic insulation, conventional and unconventional insulation materials. Embodied energy and environmental impact of the buildings can be decreased by using cellulose fibre as an insulation. Cellulose fibre can be used to control peak levels of indoor air humidity under dynamics conditions and increasing indoor thermal comfort. The mean thermal conductivity of the cellulose fibre board is analogous with materials like cork, polyurethane, recycled glass, recycled cotton and glass wool. The cellulose fibre board has a very low of mean thermal diffusivity as compared to other materials like cork, polyurethane, recycled glass, recycled cotton and glass wool. The cellulose fibre has mean thermal conductivity and mean thermal diffusivity of 0.039 W/mK and 0.046×10^{-6} m^2/s respectively. Therefore using cellulose fibre as insulation in buildings which comes under dynamic heat transfer conditions can improve the thermal comfort inside buildings and can improve energy efficiency. Additionally the cellulose fibre is a renewable, recyclable, environment friendly material and has lower embodied energy.

CRediT authorship contribution statement

R.K. Pal: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing - original draft. **Parveen Goyal:** Supervision, Writing - review & editing. **Shankar Sehgal:** Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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