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Dynamic thermal performance & economic analysis of insulation materials in temperate-Himalayan regions: A simulation-based approach

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ABSTRACT

The building sector consumes about 28% of the total world energy consumption. This is mainly consumed by the residential building sector worldwide, with a percentage of about 70%. This highlights the need to build energy-efficient buildings through passive means, where there is no additional penalty to be paid. Energy efficiency in buildings can be enhanced by adopting passive means, highly efficient and automated active means, and the renewable energy utilisation. The building envelope plays a crucial role in improving thermal performance, as it is responsible for about 50–60% of total heat loss from a building. In this study, insulation, as a means to improve energy efficiency, has been studied. Both natural and conventional insulations have been investigated in the context of the cold/temperate climate of the Himalayan region, making it a unique study of this kind. Additionally, the dynamic study of many insulation materials for both conventional and natural insulations is lacking for comparative evaluation. An uninsulated and insulated model house was numerically studied using COMSOL Multiphysics. The model house was applied with many insulations of each category of the same thickness to properly compare their thermal and economic performances. Additionally, the model house was applied with a conditional heat source to determine the heating load required to maintain thermal comfort in the house. The study concludes that both conventional and natural insulation materials significantly enhance thermal performance, reduce heating energy demand, and lower condensation risk. Among conventional options, phenolic foam and polyurethane were most effective, while natural materials like rice husk, bagasse, and kenaf offered competitive thermal benefits with superior economic returns, making them sustainable and cost-effective alternatives for building applications.

1. Introduction

In 2024, the world's energy supply and consumption were 642 EJ and 445 EJ, respectively, as shown in Fig. 1(a) and (b). The building industry consumed 124 EJ of this, with residential structures alone using 86 EJ. Furthermore, the industry produced 2,747 Mt of the 37,723 Mt of CO_2 emissions worldwide, with residential buildings accounting for 1,904 Mt of this total [1]. Due to urbanisation, technological advancements, and population growth, consumption is predicted to increase by 53% during the next 5 years. [2]. In India, the building sector consumes, 31 EJ with residential building accounting for 7.4 EJ as shown in Fig. 1(c) and (d). These figures illustrate the importance of enhancing building energy efficiency to combat climate change and achieve Net Zero Emissions (NZE). The European Union claims that the building sector has the greatest potential for energy savings [3]. This is particularly true in rapidly urbanising nations like India, where increasing population pressures exacerbate the need for energy [4,5]. India uses the most energy for construction among the countries in the Asia-Pacific Partnership (APP), and the number of new homes being built continues to increase [6]. About 79.9% of India's building stock is made up of residential structures [7], which also account for about 24% of the nation's energy consumption [1]. This makes the building sector the second-largest energy consumer in India, after the industrial sector. Residences typically consume 45% for cooling, 28% for lighting, and 12% for heating [8,9]. Around 57% of the residential energy in India is utilised for heating and cooling houses to achieve thermal comfort. Therefore, there is a very significant potential for energy conservation from the building sector in India.

Passive structures, which are designed to use as little energy as possible through material and architectural solutions, offer long-term energy savings and environmental benefits. However, their greater initial building costs and the ignorance of stakeholders remain two significant barriers to their wider implementation [10,11]. To offset the upfront costs associated with passive buildings, governments are

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