Utilization Of Nanotechnology in Construction Materials

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Abstract. The construction sector has always been one of the predominant emitters of greenhouse gases as well as the main energy consumer globally. As urban areas increased, the public's demand for housing has increased simultaneously. Eventually, the contamination and waste of energy may become more prevalent. To prevent further destruction to our environment and energy-saving process, it is an urgent need for the introduction of efficient energy-saving technology. Under this circumstance, building technology based on nanomaterials is one of the most effective approaches to reducing energy consumption. In this paper, the application of nanomaterials in the construction industry will be explored by explaining their properties and associated benefits, with special emphasis on materials including vacuum-insulated panels (VIPs) and nanogels. The results of this paper show that these properties improve their insulating abilities, hence facilitating a more efficient saving of energy. Through case analysis, it is further supported that nanomaterials have great potential to enhance efficiency and sustainability in housing construction.

Keywords: Nanotechnology; Building materials; Heat insulation.

1. Introduction

The building sector accounts for 25% of global greenhouse gas emissions and consumes 36% of available energy worldwide [1,2]. Driven by multifaceted factors in society, there is an increasing population concentration in urban areas worldwide. This phenomenon refers to global urbanization and is one of the most necessary global change processes. Due to the increase in population and the expansion of cities, the demand for housing has accelerated. Urban land consumption for purposes including available housing has outpaced population growth by 50% and is expected to add 1.2 million km^2 of new construction area by 2030 [3]. This can result in irreversible consequences, involving skyrocketing further greenhouse gas emissions and energy consumption.

Due to insufficient building insulation as well as people spending a majority of time indoors, 40% of energy consumption within housing occurred while heating or cooling buildings [4]. The energy efficiency of a building greatly depends on the performance of insulating materials used in the windows, walls, and roof. Efficient insulating materials keep indoor temperatures steady and make the temperature-regulating system work less. Without efficient insulating materials, fossil fuels are burnt to modify indoor temperature. Nevertheless, fossil fuels can aggravate air pollution that threatens the environment. To address this adverse impact brought by energy deficiency in buildings, the insulating issues should be oriented. Nanotechnology, as an emerging technology, can integrate nanomaterials into building constructions to enhance insulation performance and energy efficiency.

There is a continuing rise in temperature globally, which causes intense solar radiation. To insulate this heat, traditional materials such as polystyrene foam and glass wool function with a great thickness (250mm) and thermal conductivity of 0.6 W/(m·K) [4]. Their low efficiency and high thickness will likely increase the usage of additional cooling and heating systems. On the contrary, the ultra-low thickness and low thermal conductivity of nanomaterials make them efficient in saving energy and preventing heat loss. This article interprets the use of two particular nanotechnology in the construction industry, the vacuum insulation panel (VIP) and the nanogel. Heat loss in houses generally occurs with 35% for walls, 25% for roofs, and 10% for windows, where these nanomaterials are generally applied [5]. VIP is a kind of board-shaped panel using the insulation of a vacuum and has the lowest thermal conductivity (0.002~0.004 W/(m·K)) among current insulation technologies [4]. They are ten times more efficient than classic technologies [6]. Combined with their low thickness property, they are the most suitable materials to be used in walls, roofs, and floors even when the space is restricted. Nanogel is a kind of crosslinked hydrophilic polymer-based nanoparticle with wide surface area and low thermal conductivity 0.004–0.01 W/ (m K) [4]. They are also light and porous, making them widely used in insulation systems on windows interspace glazing.

However, the reason why these nanomaterials are not widely seen in residential buildings is that they have relatively high cost. For VIPs, they cannot be cut once they are manufactured, or the vacuum within the board will be destructed. Thus, non-standard sizes of VIPs can only be ordered to customize. This high cost keeps it far from being utilized in residential buildings. For nanogels, their prices are around 8-10 times higher than standard insulation materials. VIPs and nanogels all face the issues of high cost, therefore, to promote them in a wide range, there are still further development needs to be conducted to reduce the cost of manufacturing these beneficial materials. This article presents the remarkable properties of nanomaterials in improving the insulation performance of buildings and reveals their great potential to promote environmental sustainability. It is expected to show the advantages of nanomaterials have outweighed conventional materials. Their efficiency should support them as effective alternatives in modern material use.

2. The Utilization of Nanomaterials

2.1. Nanomaterials in Construction Industry

Nanotechnology has rapidly and extensively permeated almost all fields of science and technology in recent decades. The promotion of nanotechnology is a massive revolution to modern industries, benefiting a range of sectors including but not limited to medicine, automotive, and construction. Particularly, nanomaterials have an infinite potential to be utilized in the construction industry to modify buildings' heat-insulation properties into a more efficient and durable state and to increase their sustainability in addressing climate change and global urbanization through saving energy costs. The use of nanomaterials in the construction industry dates back to the mid-1980s and has gradually become more and more popular on a wider scale.

The utilization of nanomaterials in the construction industry can resolve existing issues in buildings, while the most significant property is its advantage in saving energy. Due to insufficient building insulation, there is a massive consumption of energy used to heat or cool buildings, spending about 36% of the overall energy produced globally [2]. New insulating materials constructed with nanotechnology offer lower thermal conductivity, thickness and improved energy efficiency, making them effective alternatives to contemporary insulating materials. The introduction of vacuum insulation panels (VIPs) and nanogel has made this trend expand.

In walls, roofs, and floors, conventional insulating materials, such as polystyrene foam and glass wool, generally function with great thickness (250mm) and high thermal conductivity of 0.6 W/(m·K) [4]. Thermal conductivity measures the easiness that which heat can travel through materials through conduction. With high thermal conductivity, the heat passes through building structures effortlessly, hence making the insulation effect deficient. Moreover, in torrid regions with intensive solar radiation, there will be an increased demand for the insulation of harsh heat. Thus, the thickness of insulating materials required will increase, which gives rise to the overall cost simultaneously. However, with nanomaterials, specifically the VIPs and nanogel, this addition in thickness and potential cost can be conceivably discarded. Compared with conventional insulating materials, the nano VIPs in walls and roofs have a low thermal conductivity (0.002~0.004 W/(m·K)) and a low thickness (5–50 mm), and a thermal resistance that is ten times higher than that of conventional insulating materials [4]. Nanogel has a low thermal conductivity of 0.004–0.01 W/ (m K) with a porous and light structure and serves as an additive in insulation coating on windows [4]. In the thermal insulation system, it effectively blocks heat from escaping. Furthermore, as the insulating performance is enhanced, there will be a prevention against extensive pollution of resources used to adjust room temperature. Without an efficient insulating system, fossil fuels such as coal and natural gas are generally burnt to ensure a moderate temperature. They burn inefficiently and release pollutants to the environment. Compared to this situation, the nano VIP can save approximately 10-20% of heating energy consumption while the nanogel glazing achieves a saving of 11% in the building's annual energy consumption [7-8]. By replacing conventional insulating materials with nanomaterials, the improved insulating efficacy reduces the demand for heating systems, thus decreasing their pollution of the environment while burning fuels. The promotion of nanomaterials effectively enhances the sustainability of housing in the environment of global urbanization.

2.2. Case Studies of Practical Usage of Nanomaterials in Internation Examples of Buildings

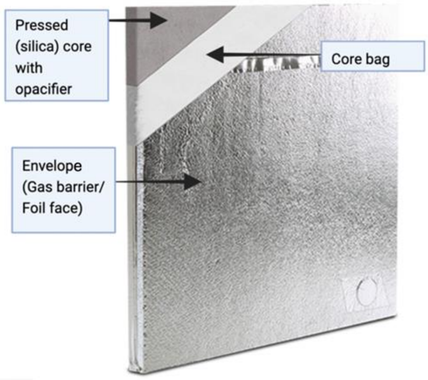

Figure 1. Components of a VIP (photo: va-Q-tec)

A nano Vacuum Insulation Panel (VIP) is an advanced and efficient thermal insulation system that can be found in buildings to insulate floors and doors. It generally consists of a core bag, an envelope, and a pressed core with an opacifier, as shown in Figure 1. The core is vacuum-filled, and the outer envelope maintains the vacuum and yields a low thermal conductivity of less than 0.004 W/ (m.K). The thermal performance of VIP relies on the envelope and the core materials optimizing the type of core material as well as maintaining a low internal pressure is essential. This low thermal conductivity was achieved by evacuating the internal air entirely to create a vacuum space. However, it is hard for a flat insulation layer to overcome the high pressure in a vacuum. As a result, the choice of porous core material for VIPs is crucial. The most commonly used core materials are precipitated silica and aerogel (silica aerogels) which have a high vacuum-level thermal resistance. Silica aerogel is a porous solid-state nanomaterial with unique properties that make it effective in thermal resistance. For instance, the silica aerogel has a low density of 0.003 g/cm3, a large surface area (500–1200 m2/g) and nanoscaled pores and a high porosity (80–99.8%) structure. These physical properties retard heat to flow into or out of a building. Compared with traditional insulating materials, a recent simulation in testing VIP's efficacy with the model of a full-scale residential house using the multiphysics software ANSYS FLUENT 2019 R2 predicted an actual saving of 13.3% lower heat loss through walls for a single house [9].

Resembling with VIPs, the nanogel also serves as an effective medium in heat resisting that is generally glazed on windows. In addition, the nanogels can incorporate nano VIPs for a combination in walls, windows, and roofs to have a greater insulation potential. Nanogels (nano-enhanced aerogel) are nanoparticles consisting of cross-bonded hydrophilic polymers. They have the properties and functions of both nanomaterials and hydrogels. Nanogels possess a high surface area, a light weight, and a highly porous structure. It also has an ultra-low thermal conductivity of 0.004–0.01 W/ (m K) [4]. They are considered one of the most cutting-edge nanomaterials to be utilized in energy-saving construction. Despite from merely an energy-efficient coating material, nanogel also provides high performance in daylight systems. Advanced daylight systems take advantage of natural light to eliminate reliance on electrical lighting systems, hence saving electric energy for daily use. Nanogel provides a 25% light transmission that maximizes the benefits of natural lights.

Regarding VIPs, with merely a thin layer of this product, there will be an increase of 8-10 times in energy efficiency in the building. Sonnenschiff Center is a building in Freiburg, Germany that combines both residential and commercial usage. It is located beside a solar housing estate and has produced advanced amenities not locally available yet. This architecture utilizes VIPs for insulation of the external walls, window guards, and ventilation flaps. With the same thickness of VIP as other conventional insulating materials, it is revealed to have a ten times better thermal insulation [10]. With the promotion of the VIPs, there is also a decline in the consumption of clean energy produced for daily usage.

A poorly insulated house can result in 25% of heat loss between seasons. The service life for VIPs is at least 25 years with a relatively low thermal resistance loss per year. With VIPs, it is ensured a more durable state of insulation within houses, thus enhancing residents' living conditions. People have done experiments to examine the resistance loss of VIPs. For instance, in Canada, the VIPs were installed on the east-facing wall of a test hut [11]. While the internal environment was controlled, the external weather data was overseen from the winter of 2010 to 2014. Under fluctuating temperatures within these four years, the thermal performance of VIPs decreased from 100% to approximately 92.5%. Compared with the 25% heat loss in poorly insulated houses, this is a significant improvement in heat-resisting efficacy maintenance in walls. The VIP's insignificant thermal performance deterioration demonstrates their great potential as insulating materials.

Heat insulation systems are extensively required in extremely hot or cold climates. In previous times, a majority of studies in insulation took place in cold areas. However, in a recent simulation of the efficacy of nanogel in 2022, it was revealed that insulating systems based on nanomaterials are considered one of the most efficient mediums in Egypt where a hot desert climate occurs. This simulation was conducted for one year with nanogel-glazed windows included within the building model. The outcome revealed a considerable reduction in cooling loads of 7.18% compared to nanogel-glazed windows with conventional glazing methods [12]. Furthermore, the simulation also involves a classroom setting demonstrating diffused light with nanogel-assist coated windows to examine their lighting performance. Eventually, it was revealed that there was a 5.23% reduction in annual electric energy consumption due to the feasible light transmission rate of nanogel [12].

Observed throughout the analysis in case studies, it is considerably noticed that architects or designers are brought to a new state of designing with materials in nanoscale. Nanomaterials benefit people by improving the structure of original materials to enhance their performance in heat insulation, thus optimizing the consumption of unrenewable energy for cooling and heating loads. Additionally, with a simultaneous improvement in lighting systems, extensive aspects of saving electric energy in the construction industry were brought to light.

3. Conclusion

Housing plays an important role in society. However, construction sectors that are in charge of the building for multifaceted-used constructions, were producing approximately one-third of the global emissions. Extensive emissions are exacerbating the occurrence of global warming and subsequent climate change. To address this issue, promoting the utilization of nanomaterials may be one of the valid resolutions. Conventional insulating systems in housing, such as polystyrene foam and glass wool, possess relatively great thickness and high thermal conductivity that make them inefficient in insulating heat compared with nanomaterials. This inefficiency potentially increases the energy consumed to heat or cool buildings with additional fossil fuels. The high durability, and low thermal conductivity of nanomaterials, particularly VIPs in walls and roofs and nanogel as an additive in insulation coating on windows, have effectively improved insulating efficacy. Eventually, the contamination brought by housing in the environment of global urbanization can be weakened. Despite their great insulating properties, the low thermal performance deterioration of VIPs and the potential use of nanogels in lighting systems create further opportunities for energy saving, making their usage durable and multifaceted. Nevertheless, to examine this technology more thoroughly, it presents not only advantages but also challenges. Nanomaterials have having high cost, making them difficult to widely utilize in residential building situations. The size of walls, windows, and roofs may differ among different houses. To fulfill residential needs, the size of VIPs may be non-standard and can only be ordered to customize. This significantly increases resident's spending on house renovation. Nanogels are also around 8-10 times higher than standard insulation materials. Consequently, to maximize the energy-saving capability and environmental sustainability of nanomaterials in the construction sector, further innovation and development in these materials should be conducted to provide greater benefits from an economic perspective, hence ensuring more accessibility for them to be widely applied in both commercial and residential buildings.

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