Proceedings of the 4th International Conference on International Law and Legal Policy
DOI: 10.54254/2753-7048/2025.LD25573

Comparative Analysis of Carbon Reduction Between Ceramic Gel Insulation and Traditional Thermal Insulation Materials

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Abstract: Against the backdrop of global efforts to address climate change and systemic change, energy conservation and emission reduction in the construction industry are of paramount importance. This study focuses on comparing ceramic gel insulation materials with traditional building insulation materials across multiple dimensions: material production, construction processes, usage phases, and the entire lifecycle. The results reveal that producing 10 million square meters of ceramic gel insulation materials reduces aggregate energy consumption by approximately 70%, and lowers carbon emissions by about 1.19×10^8 kg compared to producing the equivalent amount of traditional insulation mortar. During construction, the application time is shortened by approximately 70%, significantly reducing energy consumption and carbon emissions. In the usage phase, this material reduces energy loss by 30%. Over the entire lifecycle, the energy efficiency of ceramic gel insulation materials can be improved by 10-30%, and their overall carbon emissions are much lower than those of traditional building insulation materials. The findings of this study provide a scientific basis for the construction industry when selecting low-carbon insulation materials, promoting the industry's green and sustainable development.

Keywords: novel insulation materials, ceramic gel insulation materials, traditional insulation materials, carbon reduction comparison.

1. Introduction

With multiple indicators reaching record-high levels, our climate's dire situation calls for systemic change to our consumption choices. The construction industry is a major contributor to energy consumption and carbon emissions, accounting for a significant portion of total societal energy use [1]. Simultaneously, heating accounts for 85% of the energy used in buildings [2]. Applying thermal insulation materials helps reduce building energy consumption and generates emission-reduction effects. Therefore, building insulation is projected to play an increasingly crucial role in lowering energy consumption.

If only taking into account the demand for new buildings and the demand for existing urban housing in 2025, the market size of building insulation materials reaches RMB 199.72 billion. The selection of exterior wall insulation materials directly impacts the thermal performance and energy efficiency of buildings [3]. Research on the performance and carbon footprint of such materials

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serves to provide scientific evidence that guides private consumption, business investments, and government procurement. Traditional insulation materials, including expanded polystyrene (EPS), extruded polystyrene (XPS), polyurethane insulation boards, and rock wool, have long dominated the market but display considerable drawbacks. For instance, EPS/XPS materials typically have a B1 fire rating, indicating high fire hazards, and are susceptible to hollowing and detachment, which degrades insulation performance and increases energy consumption. Polyurethane insulation boards are toxic, and on-site foaming is inefficient. Their high cost, susceptibility to cracking, and detachment result in additional carbon emissions during maintenance and replacement. Rock wool has high water absorbency, poor durability, complex installation requirements, and high production energy consumption, giving it a high carbon footprint, which is unsuitable for achieving sustainable goals in the construction industry.

In recent years, the emergence of a novel insulation material provides a promising alternative that synthesizes thermal insulation effectiveness and low environmental impact, specifically, ceramic gel insulation material. It possesses excellent thermal insulation properties, superior fire and water resistance, and can be applied easily. A thorough comparison of the carbon reduction capabilities of ceramic gel insulation materials and traditional insulation materials contributes to achieving energy-saving and emission-reduction targets in the construction industry.

2. Challenges and current status of traditional thermal insulation materials

Currently, common exterior wall insulation systems in China include external wall insulation, internal wall insulation, sandwich wall insulation, and self-insulating walls. Considering its effectiveness in limiting thermal bridging, compatibility with interior renovations, and convenience of applying on old buildings, external wall insulation remains the dominant approach in most construction projects [4].

Traditional exterior wall insulation materials typically exhibit high thermal conductivity and limited insulation effectiveness. Under extreme weather conditions, these materials fail to effectively hinder heat transfer, leading to increased indoor temperature fluctuations and energy consumption. Additionally, the subpar fire resistance and complex installation requirements of traditional materials restrict their broader application. In harsh environments (e.g., high temperatures or humidity), traditional insulation materials are likely to become inefficient, and some of them, such as vacuum insulation panels, require precise installation with seamless intersections, which means that inaccuracy during human construction can significantly limit their performance [5].

In renovation projects of older buildings, traditional insulation materials are also confronted with compatibility issues. Some are too heavy to be supported by old walls or limited by spatial constraints, while others suffer from poor durability, being susceptible to aging and performance degradation due to exposure to ultraviolet light, temperature changes, and moisture. This leads to risks like hollowing, cracking, and detachment, which necessitates frequent maintenance and is therefore inconsistent with long-term goals of reducing costs and emissions.

The production of traditional insulation materials is often extremely polluting. Polyurethane foam, for instance, contains volatile organic compounds (VOCs) or Freon blowing agents, both of which are currently restricted under regulations such as the EU REACH and China's green building standards. Some of the other materials, like ceramic fiber, require high-temperature sintering during production, resulting in substantial energy consumption that conflicts with carbon neutrality goals.

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3. Overview of ceramic gel insulation materials

3.1. Technical principles

The first of the core components of ceramic gel insulation materials is aerogel. Recognized as one of the most promising high-performance insulation materials in the construction industry, aerogel exhibits exceptional thermal insulation properties compared to traditional materials, featuring the lowest refractive index and dielectric constant among all solid materials [6]. It is already being adopted in industrial thermal pipelines (replacing bulky traditional materials) and the aerospace industry (NASA uses it for cryogenic tank insulation), where its lightweight and application flexibility give it a prominent edge over competing candidates.

Ceramic gel insulation materials are produced by combining ceramic vacuum microspheres with aerogel, both of which have extremely low thermal conductivity. This combination efficiently blocks infrared radiation and conductive heat transfer, giving it an insulation efficiency of up to 90%. When applied, the material forms a vacuum-like matrix layer that effectively blocks external heat radiation, which maintains comfortable indoor temperatures and significantly reduces indoor energy consumption. Figure 1 illustrates the insulation principle.

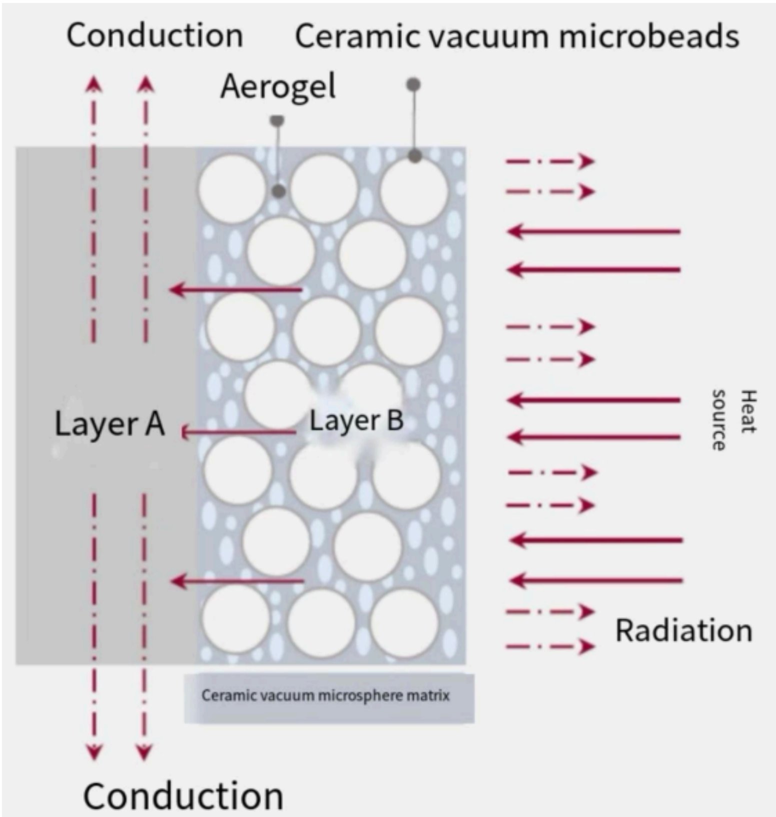

Figure 1. Schematic diagram of insulation principle

3.2. Technical features

Ceramic gel insulation materials present numerous advantages. They achieve a Class A fire rating, which means that they are non-combustible according to China's building material fire safety classification system (GB 8624 standard), effectively containing fire spread to ensure the safety of

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lives and property. The materials are also surprisingly resilient to water and mold, protecting walls from moisture damage and extending their service life.

The application process is simple and highly efficient, mostly comprised of spraying or rolling methods that permit a team of workers (2-3 men) to cover 500–1,000 square meters per day. The construction period is shortened by approximately 70% compared to that of traditional insulation materials. Moreover, the material's flexibility allows it to resist substrate deformation, adapt to various surface shapes, and prevent wall cracking.

4. Comparative analysis of carbon reduction between ceramic gel and traditional insulation materials

4.1. Comparison of energy efficiency coefficients

A critical parameter for evaluating insulation material is thermal conductivity (λ), which, denoted by $\lambda = \frac{Qd}{A\Delta T}$, measures the material's ability to conduct heat [7]. China's energy code (GB/T 10295-2008) and the international standard (ISO 10456:2007) classify materials based on thermal conductivity. Categories include conventional insulation (0.035–0.065 W/m·K), highly efficient insulation (0.025–0.035 W/m·K), and ultra-efficient insulation (< 0.025 W/m·K). Ceramic gel insulation materials excel in this regard, with thermal conductivity typically ranging between 0.015–0.025 W/(m·K) under regular conditions, and high-quality products achieving values as low as 0.01 W/(m·K). In contrast, traditional materials such as EPS/XPS (0.035 W/(m·K)), polyurethane boards (0.024 W/(m·K)), rock wool (0.040 W/(m·K)), insulation mortar (0.070 W/(m·K)), and homogeneous boards (0.060 W/(m·K)) exhibit higher thermal conductivity.

To measure a particular piece of material's overall ability to resist heat transfer, scholars can calculate its heat resistance using $R = \frac{d}{\lambda}$, which is to divide a material's thickness by its thermal conductivity. Thanks to its low thermal conductivity and unique microstructure, ceramic gel insulation materials form an efficient thermal barrier. Achieving the same insulation effect requires thinner layers compared to traditional materials, saving space while enhancing overall system performance. It is efficient in reducing heat transfer between indoor and outdoor environments, thereby lowering energy consumption for indoor temperature regulation.

In terms of fire safety, ceramic gel insulation materials also outperform traditional options. With a Class A rating, they are categorized as non-combustible, which outperforms EPS/XPS and polyurethane boards (Class B1). This makes them ideal for projects with stringent fire safety requirements. Table 1 summarizes the thermal conductivity, thermal storage coefficient, and fire rating for different thermal insulation materials, offering a quick reference for their thermal performance and fire safety characteristics.

Table 1. Energy efficiency coefficient comparison

	Thermal Conductivity (W/m·K)	Thermal Storage Coefficient (W/m²·K)	Fire Rating
Ceramic Gel	0.01-0.025	≥1	A
EPS/XPS Board	0.035	0.45	B1
Polyurethane Insulation Board	0.024	0.35	B1
Rock Wool	0.040	0.95	A
Thermal Insulation Mortar	0.070	1.20	A
Homogeneous Board	0.060	1.00	A2
STP (Super Thin Panel)	0.010	0.30	A

4.2. Comparison of carbon emission in the production phase

This part will compare the carbon emissions of producing ceramic gel insulation materials with those producing rock wool, considering the latter's broad application in modern construction and renovation. Although the carbon footprint of producing the same mass of ceramic gel insulation materials and rock wool is similar, the low thermal conductivity of ceramic gel gives it a higher equivalent thermal resistance, therefore reducing the amount of materials required for covering a given area of external wall and reducing carbon emissions.

China's "Design Standard for Energy Efficiency of Public Buildings" (GB 50189) divides China into climate zones while setting distinct thermal resistance requirements for exterior walls. This comparison adheres to the requirements of "Cold Zone B", which requires the minimum wall thermal resistance to be greater than 1.0(m²·K)/W. To calculate the carbon footprint of producing the materials that achieve a thermal resistance (R-value) of 1.0 (m²·K)/W over a 1 m² area, the analysis first calculates the required thickness (d) of each material using its thermal conductivity (λ) and the target R-value. It then determines the mass of the material based on its density (ρ) and calculated thickness. Lastly, it estimates the carbon footprint by multiplying the material mass by its production-specific carbon intensity (kg CO_2 eq/kg). The key formulas are: $d = \frac{\lambda}{R}$, $m = \rho \times d \times A$, and Carbon Footprint=m×Carbon Intensity, where $A=1m^2$. The following calculations are based on industry reports.

Ceramic gel has a thermal conductivity (λ) of 0.01 W/(m·K) and a density (ρ) of 350 kg/m³. The required thickness to achieve R=1.0 (m²·K)/W is 0.01m(10mm). The mass of ceramic gel required is m=350×0.01×1=3.5kg. Given that the production of 1 ton (1000 kg) of ceramic gel emits approximately 1660 kg CO_2 eq, the carbon intensity is 1.66 kg CO_2 eq/kg. The total carbon footprint for producing 3.5 kg of ceramic gel is 3.5×1.66=5.81kg CO_2 eq [8].

Rock wool has a thermal conductivity (λ) of 0.04 W/(m·K) and a density (ρ) of 150 kg/m³. The required thickness to achieve R=1.0 (m²·K)/W is 0.04m(40mm). The mass of rock wool required is m=150×0.04×1=6kg. Given that the production of 1 ton (1000 kg) of rock wool emits approximately 1490 kg CO_2 eq, the carbon intensity is 1.49 kg CO_2 eq/kg. The total carbon footprint for producing 6 kg of rock wool is 6×1.49=8.94 kg CO_2 eq [9].

The results show that ceramic gel requires a thinner layer (10 mm) compared to rock wool (40 mm) to achieve the same thermal resistance, due to its lower thermal conductivity. This translates to a lower mass (3.5 kg vs. 6 kg) and, consequently, a 28.3% reduction in carbon footprint (5.81 kg CO_2 eq vs. 8.94 kg CO_2 eq) for ceramic gel. The superior thermal performance of ceramic gel reduces the material thickness and mass needed, amplifying the benefits of its lower production-

DOI: 10.54254/2753-7048/2025.LD25573

phase carbon intensity (1.66 kg CO_2 eq/kg vs. 1.49 kg CO_2 eq/kg). While rock wool is a widely used and cost-effective material, ceramic gel offers a more environmentally sustainable alternative for applications that prioritizes low carbon emissions and has sufficient funding.

4.3. Comparison of carbon emission in the construction phase

Ceramic gel insulation materials also demonstrate significant advantages in terms of energy consumption and carbon emissions during construction. The application process is incredibly straightforward. Current techniques primarily involve spraying and rolling, which is highly efficient compared to the application of traditional insulation materials. It requires no complex equipment or extensive labor, and the shortened construction period further reduces energy use and emissions.

In stark contrast, traditional insulation materials, call for complex installation processes and are prone to detachment. For example, EPS/XPS installation requires mortar leveling, which consumes 0.5–1 kWh of electricity per square meter. The adhesive used for bonding insulation layers also has high production energy demands, generating 0.3–0.5 kg of carbon emissions per square meter. Additional steps, such as installing plastic anchors, applying crack-resistant mortar, and embedding alkali-resistant fiberglass mesh, further increase energy use. Equipment like suspended platforms consumes 3–5 kWh per hour, and their transportation and rental add to the carbon footprint. Table 2 provides a concise overview of the construction processes, key features, and associated issues for the previously mentioned thermal insulation materials.

Table 2. Comparison of construction processes

Material Name	Construction Overview	Key Features/Issues
Ceramic Gel	Base check → Coat → Insulate → Finish	Simple, quick; Water/mold/fire/crack-proof; Cost-effective
EPS/XPS Board	Level → Bond EPS → Protect → Surface	High fire risk; Prone to hollowing/detachment
Polyurethane Board	Level → Bond PU → Protect → Surface	Toxic, foaming banned; Costly, short-lived, prone to issues
Rock Wool	Treat base → Bond → Spray → Plaster → Mesh → Mortar → Surface	High water absorption, demanding construction
Integrated Panel	Treat base wall → Mark → Glue → Install → Fix → Seal → Clean	Expensive, short lifespan, poor value
Insulation Mortar	Interface → Add particles → Mortar → Mesh → Mortar → Coat	Thick, prone to issues; Microspheres break; Height limits
Homogeneous Board	Treat base wall → Mix glue → Install → Seal → Surface	Moisture-sensitive, ages, harmful combustion
STP Panel	Treat base wall → Mark → Install bracket → Install → Secure → Mortar → Surface	Can't cut on-site; Complex, high difficulty

4.4. Carbon emission comparison in the usage phase

Due to their low thermal conductivity, ceramic gel insulation materials significantly reduce heat loss, enhancing the thermal performance of exterior walls. By reducing heat transfer between indoor and outdoor environments, they reduce the energy required for heating in winter and curtail the frequency and duration of air conditioning use in summer, thereby diminishing building energy consumption and carbon emissions.

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For example, a project in Zhejiang using ceramic gel insulation materials achieved a 30% reduction in energy loss. In contrast, traditional insulation materials, with their unstable performance, fail to effectively block heat transfer under extreme weather conditions, leading to higher energy use and emissions.

4.5. Comprehensive lifecycle carbon emission comparison

The thermal performance and structural safety of exterior wall insulation are heavily dependent on the quality of materials. High-quality materials improve insulation efficacy and extend service life [10]. Traditional materials, due to poor durability, require frequent maintenance and replacement, increasing lifecycle energy use and carbon emissions. For instance, traditional insulation mortar has a short replacement cycle, and its declining performance over time leads to rising energy consumption.

By contrast, ceramic gel insulation materials have a service life exceeding 20 years and improve energy efficiency by 10%-30%. Their low production energy use, efficient construction, and superior performance result in significantly lower lifecycle carbon emissions compared to traditional materials.

5. Policy advice for Chinese government procurement of thermal insulation materials

To promote sustainable development and energy efficiency in China's construction sector, it is crucial to adopt targeted policies for government procurement of thermal insulation materials. Based on the considerations while selecting insulation materials, China’s vast territory can be divided into three regions: cold regions, hot summer and cold winter regions, and hot summer and warm winter regions.

5.1. Cold regions (e.g., northeast, northwest, Tibet)

This region covers most of the area north of the Qinling-Huaihe line, and includes most of Xinjiang, northern Gansu, Tibet, and western Inner Mongolia. These areas typically have extremely dry and cold winters, with temperatures often dropping below -15°C and occasionally reaching -30°C. The application of insulation materials in this region lowers energy consumption for heating and ensures that buildings remain warm and energy-efficient during harsh winters. The primary requirements for insulation materials are high thermal resistance to minimize heat loss, high fire-resisting qualities to prevent fire catastrophes, and the ability to resist extremely low temperatures. Ceramic gel insulation materials exhibit extremely low thermal conductivity (0.010-0.025 W/(m·K))and the best fire resistance rating possible(Class A), which reliable fire safety that is crucial in densely populated areas. Additionally, their moisture resistance helps prevent degradation due to occasional snowfall and rain, ensuring long-term performance.

5.2. Hot summer and cold winter regions (e.g., central, east, and south China)

The hot summer and cold winter region roughly covers the area south of the Longhai Railway and north of the Nanling Mountains, east of the Sichuan Basin, and can also be roughly described as the middle and lower reaches of the Yangtze River. It involves 16 provinces, municipalities, and autonomous regions, and is the region with the densest population and relatively developed economy and culture in China. The significant temperature variations in this region, both between day and night and between seasons, require insulation materials to be versatile, providing effective thermal insulation in both hot and cold conditions while resisting moisture. Ceramic gel insulation materials, with their low thermal conductivity and excellent moisture resistance, are well-suited for maintaining a stable indoor temperature, reducing the need for heating in winter and cooling in summer, thereby lowering energy consumption and carbon emissions.

However, Government procurement policies should consider combining the use of ceramic gel with traditional materials that have a higher coefficient of thermal storage, due to the large difference in night and day temperatures. A higher heat storage coefficient means that the material can absorb and store more heat. During the day, when the outside is hot, the material absorbs and stores heat, slowing down the rate at which the indoor temperature rises. At night, on the other hand, when the outside temperature drops, the materials slowly release the stored heat, which helps maintain a relatively stable indoor temperature, reduces the usage time of air conditioners and other refrigeration equipment.

5.3. Hot summer and warm winter regions (e.g., south China, Hainan, Taiwan)

The hot summer and warm winter regions are located in the southern part of China, including most of Guangdong, most of Guangxi, southern Fujian, Hainan, as well as Hong Kong, Macao, and Taiwan. The population of this region is approximately 150 million, with a relatively high living standard that is extremely energy-consuming. It is the focus of Chinese building energy conservation work. In these regions, summers are long and extremely hot, with high humidity, while winters are mild. Since indoor heating is non-existent, the primary focus for insulation materials is to prevent outside heat from entering the cool indoors to reduce cooling loads and prevent mold growth. Ceramic gel insulation materials, with their low thermal conductivity and high solar reflectance, can effectively achieve this goal, minimizing the reliance on air conditioning. Their moisture resistance also helps maintain a dry and healthy indoor environment.

6. Conclusion

Ceramic gel insulation materials outperform traditional materials by lowering energy use and emissions during the production phase, simplifying the application process and reducing energy use during the construction phase, and significantly saving energy by effective insulation during usage, all of which gives it a life cycle carbon footprint that is far lower than alternatives. Simultaneously, these materials offer superior fire resistance, waterproofing, mold resistance, and durability, addressing key drawbacks of traditional materials while enhancing building safety and quality.

As energy-saving and emission-reduction requirements grow, novel insulation materials like ceramic gel insulation will see broader adoption. Their promotion will drive the construction industry toward low-carbon, green development. Future efforts should focus on R&D to optimize performance, reduce costs, and enhance market competitiveness. The industry must also raise awareness, establish standards, and encourage widespread use of these materials to support established Nationally Determined Contribution goals.

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