# Challenges and Prospects of Building Thermal Insulation Coatings in the Low-Carbon Transition

Mingshuo Li[a], Jiashuo Zhang[b], Yunxiang Lu[c], Jun Zhang[d]

School of Civil Engineering and Architecture, Xinjiang University, Urumqi 830047, China

[a]2296188661@qq.com, [b]2995637760@qq.com, [c]3225634240@qq.com, [d]2147773857@qq.com

**Abstract.** Global building energy consumption accounts for approximately 35% of total energy use, with its full-life-cycle carbon emissions emerging as a critical factor in achieving carbon peaking and neutrality goals. In China, for instance, operational building carbon emissions exceed 50% of the national total, while thermal losses through building envelopes in extreme climate zones like Xinjiang contribute over 50% of total energy consumption, underscoring the pivotal role of thermal insulation coatings in energy conservation. This review systematically examines conventional thermal insulation coating systems—including barrier-, reflective-, and radiative-type technologies—based on their porous structural optimization, high-refractive-index filler composites, and atmospheric window spectral regulation mechanisms. It further introduces emerging functional coatings: phase-change types utilizing microencapsulation to address leakage constraints, bioinspired coatings mimicking biological thermal management through hierarchical micro-nano structures, eco-friendly variants employing bio-based materials to reduce environmental impact, and transparent coatings balancing optical transparency with thermal insulation via nanocomposite engineering. However, current systems face persistent challenges including multi-scale interfacial instability, process cost-effectiveness limitations, and insufficient cross-climate service performance databases. Future research must prioritize breakthroughs in dynamic thermal-responsive smart materials, high-throughput directional assembly processes, and innovative full-life-cycle carbon accounting methodologies. These advancements will promote the evolution of building energy efficiency toward adaptive regulation and ecological sustainability, offering systematic solutions to support global carbon neutrality objectives.

**Keywords:** Building Energy Efficiency; Barrier-Type Coatings; Reflective Coatings; Radiative Coatings; Phase Change Coatings; Bio-Inspired Coatings; Transparent Coatings.

The global construction sector accounts for 34%-36% of total energy consumption and serves as a key contributor to carbon emissions, particularly due to air conditioning and heating systems[1][2]. In China, buildings' lifecycle carbon emissions represent 50.9% of the national total, with operational energy use constituting 21.8%. Notably, public buildings in Xinjiang of China exhibit 2.5-3.2 times higher energy consumption intensity per unit area than residential buildings[3][4]. Intense summer solar radiation causes significant heat gain through building envelopes, contributing over 50% of total energy consumption in extreme climate zones[5]. Enhancing the thermal insulation of building envelopes and accelerating their low-carbon transition are urgently required to achieve carbon neutrality goals.

Traditional building envelope insulation materials face limitations such as complex installation, thermal bridging at joints, performance degradation from moisture-induced pulverization, and flammability risks of aging organic materials. In contrast, emerging thermal insulation coatings achieve efficient heat resistance through submillimeter-thin layers with low thermal conductivity, high infrared reflectivity, and emissivity. Their lightweight nature, easy application, and adaptability to complex facades make them particularly suitable for existing building retrofits. Despite challenges like high costs and inadequate weather resistance in humid-heat/salt-mist environments, these coatings demonstrate significant potential for energy conservation under carbon neutrality goals. This paper systematically reviews research progress in traditional insulation coatings, summarizes advances in novel solutions, and outlines future directions to advance their application in building energy efficiency.

# 1. Principles and Classification of Traditional Thermal Insulation Coatings

According to the different thermal insulation mechanism and mode of thermal insulation coating, the traditional thermal insulation coating can be divided into three types: barrier type, reflective type and radiation type.

## 1.1 Barrier type thermal insulation coating

Since its development in the 1980s, barrier coatings represented by composite silicate systems have formed a typical formula system. During construction, a continuous insulation layer is formed on the surface of the substrate using a 5-20mm thick coating process. Its performance mainly depends on the synergistic effect of the thermal conductivity of the filler and the pore structure of the coating. The insulation effect is positively correlated with the increase of thickness, and is particularly suitable for high-temperature protection of building exterior walls in summer[9][10].

### 1.1.1 Thermal insulation principle

Barrier type thermal insulation coating is a functional material that achieves passive temperature control by reducing heat conduction. Its core mechanism is to use low thermal conductivity components and porous structures to form significant heat transfer impedance. This kind of coating is usually composed of lightweight thermal insulation aggregate (such as aerogel, hollow glass beads, expanded perlite), low-density inorganic mineral filler (diatomite, vermiculite, sepiolite powder) and weather resistant binder (organic resin or silicate cementitious materials). The thermal conductivity of the coating is reduced by introducing non convection air with low thermal conductivity to build a loose structure with high porosity[6],[12][13].

In order to reduce the thermal conductivity of the thermal insulation coating, different people at home and abroad have done a lot of research on improving the performance of the coating through different methods, such as sol-gel method, solid phase reaction method, micro phase structure control, in-situ crosslinking, filler modification, physical blending method, in-situ polymerization, layer by layer deposition, air pressure spraying process and phase inversion method[18-28].

Silica aerogel shows good thermal insulation and sound insulation performance, mechanical strength and optical transparency, and has been used in the preparation of thermal insulation coatings in recent years[17].Xu et al[18]The SiC coating prepared on the surface of mullite fiber was compounded with sol, and then aged and supercritical dried to prepare a shielding $Al_2O_3$-$SiO_2$ aerogel thermal insulation composite with a thermal conductivity of 0.049W/(m • K) at 1000℃.Lu et al[19]A lightweight nanocomposite with density of 0.13g/cm3 and thermal conductivity of 0.024W/(m • K) was prepared by adjusting the density of microstructure and the in-situ crosslinking between silica aerogel and boroaluminosilicate fiber during thermal compression.Ding et al[20]$TiO_2$ aerogels were prepared by sol-gel method, and then blended with $SiO_2$ sol. $SiO_2$/$TiO_2$ composite aerogels with room temperature thermal conductivity as low as 0.0251W/(m • K) were prepared by electrospinning and freeze casting technology.Luo et al[21]By using physical blending method, gas-phase silica, $Al_2O_3$ and $MnO_2$ are efficiently combined, and their synergistic effect is utilized to achieve a thermal conductivity of 0.0843W/(m • K) at 500℃ and a temperature resistance limit of 1200℃ for the thermal insulation coating.Zheng et al[22]The silica dry gel is integrated into the acrylic lotion through in-situ polymerization technology, and the thermal conductivity of the coating is reduced to 0.07 W/(m • K). This direct synthesis of silica dry gel in the acrylic lotion effectively simplifies the preparation process of the dry gel thermal insulation coating.

In addition to silica aerogels, rare earth oxides, hollow glass beads and nanomaterials have also been extensively studied due to their excellent thermal insulation properties and their synergistic effects.Li et al[23]A high entropy pyrochlore type structural material based on rare earth zirconate was successfully prepared by mixing six rare earth oxides in equimolar ratios with $ZrO_2$ using traditional solid-phase reaction method, with a thermal conductivity continuously below 1W/(m·K) in the temperature range of 300-1200°C.Yan[24]A low thermal conductivity and weather resistance coating with a thermal conductivity of 0.0712W/(m·K) and an adhesion of 1.57 MPa was prepared with modified acrylic lotion and inorganic zinc silicate resin as the matrix, in cooperation with vitrified beads, glass fiber and titanium powder.Zhang et al[25]By combining layer by layer deposition technology with pressure spraying process, a highly ordered $Ca_2Nb_3O_{10}$ nanosheet based thermal insulation coating with corrosion and oxidation resistance was successfully prepared, which exhibited a minimum ultra-low thermal conductivity of 0.03W/(m·K) after annealing at different temperatures.Zhang et al[28]Phenolic epoxy lotion was prepared by phase inversion method, and hollow glass microspheres (HGMs) were added to it as thermal insulation filler to prepare water-borne thermal insulation coating with thermal conductivity as low as 0.093W/(m·K).

### 1.2 Reflective thermal insulation coating

Reflective thermal insulation coatings originated from aluminum based reflective insulation systems, which achieve high visible light reflectivity by introducing metals and oxides (such as $Al_2O_3$) as functional fillers[13].However, metal fillers are prone to oxidation reactions in aqueous media, leading to optical performance degradation, and are therefore limited outside of building insulation systems[14].This type of coating combines the advantages of high substrate adhesion, environmental weather resistance, and surface self-cleaning, and can be directly applied to the surfaces of crude oil storage tanks, refrigeration equipment, and building envelope structures without the need for auxiliary protective layers[13].

### 1.2.1 Thermal insulation principle

Reflective thermal insulation coatings achieve cooling by reflecting over 95% of solar radiation in the visible and near-infrared spectrum. Their core composition combines a high-transparency resin binder with high-refractive-index fillers and hollow microspheres: Metal oxides induce surface reflection through refractive-index mismatch with the resin matrix, while hollow materials trigger secondary scattering via low-thermal-conductivity porous structures, synergistically blocking heat transfer. The coating’s reflectivity is directly governed by the refractive-index difference between binder and fillers, particle size distribution, and filler concentration, with greater refractive-index gaps amplifying interfacial reflection efficacy[6],[15],[16].

### 1.2.2 Research progress

To reduce the absorption of solar radiation by buildings and focus on mitigating the urban heat island effect. Usually, solar reflective pigments such as $TiO_2$ and ZnO particles are embedded in polymer matrices[26][27].Among them, titanium dioxide, due to its high reflectivity, has been extensively studied by scholars at home and abroad in recent years for its synergistic effects with different types of substances such as $SiO_2$, graft copolymers, Fe, etc[29-37].For example, Hong [33]A new type of potassium silicate based solar thermal reflective coating with a thermal reflectance exceeding 90% was successfully prepared using mechanical activation and polyester (PET) fiber toughening technology, with potassium silicate as the base material, $TiO_2$ as the pigment, and $AlPO_4$ as the curing agent.Liu et al[34]$SiO_2$ shell was prepared by template method, and $TiO_2$ nanoparticles were deposited on the surface of $SiO_2$ by hydrothermal method to form a porous shell. Finally, the dispersion was coated on a glass substrate using drop casting method to make a coating. After testing, the infrared reflectivity was 89.61%.Yu et al[37]Using bisphenol A diglycidyl ether as the film-forming substrate, $TiO_2$ as the main reflective material, and adding 9 wt% bismuth vanadate/iron oxide yellow composite pigment, an environmentally friendly reflective coating with visible light reflectivity of 53.26%, near-infrared reflectivity of 76.85%, and brightness value of 81.55 was prepared, which combines cooling and driving safety.

At the same time, in order to meet the aesthetic needs of diverse colors, the development of colored coatings is also quite important. Different scholars have conducted extensive research on reflective coatings in coatings and their production into reflective coatings[38-40].Chen et al[41]In this study, yttrium aluminum garnet was modified by cerium doping by sol-gel method, and a new type of thermal insulation ceramic pigment with high near-infrared reflectance, ultra-low thermal conductivity and bright yellow color was developed.Luo et al[42]Using traditional solid-state reaction method, a new type of inorganic pigment with adjustable color and a reflectivity of 87-98% at a wavelength of 1100 nm was prepared by mixing and grinding lithium, aluminum, molybdenum oxides, and doped metals (Fe, Pr, etc.) as raw materials, and calcining them at a high temperature of 650 ℃ .Yu et al[43]By environmentally friendly hydrophobic modification, hollow glass microspheres, $TiO_2$, and inorganic composite pigments with high near-infrared reflectivity were mixed and sprayed to prepare superhydrophobic insulation coatings with near-infrared reflectivity of 0.833, 0.797, and 0.646 for yellow, brown, and black, respectively.

For the problems of poor weather resistance and insufficient high-temperature stability in traditional organic based reflective coatings, research has turned to inorganic substances such as potassium titanate, kaolin, and mullite to innovate the traditional system.For example, Lu[44]Potassium titanate whiskers (PTW) were prepared by KDC method, and $TiO_2$ was modified by allyl bromide. At the same time, a core-shell $TiO_2$ @ PA hybrid lotion was designed by fine lotion polymerization, and PTW with a solar reflectance of 0.86 was prepared by compounding PTW and $TiO_2$@ PA/ $TiO_2$@PA Reflective thermal insulation coating.Gomez et al[45]A reflective coating based on mullite reverse photonic glass (PhG) was developed by combining sol gel with atomic layer deposition (ALD) technology. The coating still maintains high near-infrared reflectance and structural stability at 1500 ℃.Ragi, etc[46]In response to the insufficient solar thermal shielding performance of polyurethane (PU) protective coatings, kaolin functional fillers were prepared by surface modification of alumina/zirconia combined with colloidal oxides, effectively improving their infrared reflection ability.

Table 1 Performance Comparison of Commonly Used Reflective Fillers

| Material | Refractive Index | References |
|---|---|---|
| Titanium Dioxide rutile $TiO_2$ | 2.74 | [47][48][49] |
| Anatase $TiO_2$ | 2.57 | [47][48][49] |
| $SiO_2$ | 1.54 | |
| Iron Oxide Pigment | 1.7（blue）<br>2.05（red）<br>1.80（green）<br>2.41（yellow）<br>1.60（orange）<br>1.44（borrow） | [50] |
| ZnO | 1.6 | [51] |

### 1.3 Radiation type thermal insulation coating

Unlike passive thermal reflection in barrier or reflective coatings, this material enables bidirectional thermal management: absorbing 45%-60% of visible light via lattice vibrations during solar exposure, then releasing over 70% of stored heat through radiative emission post-thermal equilibrium, achieving simultaneous internal and external cooling.

#### 1.3.1 Thermal insulation principle

Radiation type thermal insulation coating is an active cooling material based on thermal radiation effect. Its core mechanism is to convert the absorbed solar energy (mainly concentrated in the 0.4-2.5 μm band) into electromagnetic waves of specific wavelengths through the energy state transition of material molecules, especially in the atmospheric infrared window band of 8-13.5 μm, to dissipate heat or thermal radiation into the cold universe (≈ 3K)[6].Due to the low absorption rate of water vapor and carbon dioxide, this band can achieve 70% -95% of thermal energy penetrating the atmosphere and dissipating into outer space, forming a unique "escape channel" for thermal energy[16].Passive radiative cooling technology does not require energy input and cools surfaces by reflecting sunlight and radiant heat, which has a significant impact on the global energy landscape[7].

### 1.3.2 Research progress

In the early days, in order to achieve high solar reflectivity and passive radiative cooling, multi-layer mirror structures were often constructed using thin layers of metals such as silver and aluminum. However, these coatings have limitations such as narrow optical reflection bands, poor mechanical durability, and a mirror like appearance that may not be visually appealing[53-55].In recent years, researchers have gradually shifted from traditional metal based multilayer structures to materials such as polymers, inorganic/ceramic substrates, and dielectrics[56-63].For example, Shao et al[56]A $WSi_2$-Si-glass hybrid coating with good thermal durability was prepared on a fiber $ZrO_2$ ceramic substrate using an impregnation rapid sintering process with $WSi_2$ as the emitter, borosilicate glass as the binder, and Si and $SiB_6$ as sintering aids.Chen et al[57]A precursor solution was prepared by physical blending using $H_3PO_4$, Al $(OH)_3$, and deionized water. Zirconia balls were used as a medium to ball mill the metakaolin powder and precursor solution. Finally, the slurry was sprayed onto an aluminum plate to prepare a 0.95 high emissivity and excellent durability all inorganic radiation cooling coating based on phosphate based geopolymer (PGEO).Guo et al[63]The silicone resin/boron nitride dielectric radiation cooling material designed through biomimetic dynamic hydrogen bonding network has a synergistic mechanism of crack self repair and fracture energy enhancement, significantly improving its outdoor durability while maintaining high radiation cooling performance.

In recent years, polymer materials represented by polydimethylsiloxane (PDMS), polyvinylidene fluoride (PVDF), and their copolymers (such as [P (VdF HFP) $_{HP}$]) have attracted much attention in the field of building insulation due to their unique photothermal control properties[58-62].

Mishra, BR, etc[58]A disordered $TiO_2$/PDMS metamaterial coating with 0.94 solar reflectance and 0.96 atmospheric window emissivity was developed by randomly embedding monodisperse $TiO_2$ microspheres into a polydimethylsiloxane (PDMS) matrix.Xiang et al[60]$SiO_2$ microspheres were embedded into a three-dimensional porous cellulose acetate (3DPCA) matrix using phase change technology and automatic deposition method to prepare thermal insulation coatings with an average emissivity of 0.96-0.97, which can be applied in various fields such as building energy conservation.Das,P[62]A radiation insulation coating based on MgO polyvinylidene fluoride (MgO-PVDF) with an emissivity of up to 0.985 has been developed. However, the production cost of PVDF is relatively high,Based on this, Tian et al[61]Polyethylene terephthalate (PET) and a small amount of polyolefin were prepared into PET/polyolefin prefabricated films through ultra large scale and high-throughput film stretching methods. A layer of polymethyl methacrylate (PMMA) micro hemisphere was coated on top of it to develop a low-cost and 0.901 emissivity PMMA hemispherical coating.

## 2. New type of thermal insulation coating

### 2.1 Phase change materials

Phase change materials (PCMs) regulate temperature through solid-liquid phase transitions to absorb/release heat, and are applied to building envelopes and roofs to enhance thermal inertia [64]. Despite their high latent heat density and temperature regulation capabilities, liquid-phase leakage-induced poor cyclic stability severely hinders practical applications. In recent years, scholars have combined microencapsulation technology with porous matrix adsorption strategies to optimize thermal performance while suppressing leakage.For example, Wang Qinghua and others[65]Using high-density polyethylene (HDPE) to encapsulate paraffin and utilizing the rigid shell of HDPE to restrict liquid phase flow;Wu [66]Then the double encapsulation method of vitrified beads vacuum adsorption and styrene acrylic lotion is proposed to improve the sealing performance through physical adsorption and polymer coating.Zhang et al[67]Coating and encapsulating PCMs using the high crosslinking properties of epoxy resin.Mohammadreza et al[68]Phase change materials (PCMs) were encapsulated in a urea formaldehyde (UF) shell and dispersed in a polydimethylsiloxane (PDMS) matrix using in-situ polymerization technology.

## 2.2 Biomimetic coatings

In recent years, biomimetic thermal regulation research has made significant progress in areas such as radiation cooling, hydrophobic insulation, and extreme environmental protection by drawing on the structural and functional characteristics of natural organisms.Norman and others[69]Based on the biomimetic research of the Sahara silver ant triangle hair array, it is revealed that it suppresses solar radiation heat absorption through high reflectivity in the visible near infrared band, while enhancing black emissivity in the mid infrared atmospheric window, and utilizing passive radiation cooling effect to dissipate heat to space and other dual thermal regulation mechanisms. However, the synergistic regulation of broadband reflection narrowband emission and large-scale controllable preparation technology of micro nano structures have not yet been solved.Kulp et al[70]Research has found that the multi-level micro nano structure formed by β - keratin nanofibers in penguin feathers achieves synergistic optimization of thermal insulation and superhydrophobicity on the basis of lightweight design, providing a natural paradigm for the design of biomimetic lightweight thermal insulation hydrophobic integrated materials.Metwally et al[71]By systematically analyzing the microstructure of penguin feathers and polar bear hair, quantitative analysis based on scanning electron microscopy (SEM) revealed that both have typical layered porous structures that can significantly improve the thermal resistance of hair. Their effective thermal conductivity is as low as 0.023 W/m • K, which is 40% lower than traditional insulation materials.Zhan et al[72]Inspired by the hollow, lightweight and hydrophobic characteristics of polar bear hair, which can withstand extremely cold environments, a carbon tube aerogel with advantages of lightweight, waterproof and thermal insulation was developed, and its performance is better.Li et al[73]By mimicking the layered structure of pearl shells and using a radio frequency magnetron sputtering system to control the shutter time of dual sputtering guns, excellent high-temperature and wear-resistant CrMoN/SiNx multilayer coatings were prepared.Miguel and others[74]Based on the high reflectivity characteristics of the Sahara silver ant and the spatial distribution pattern of zebra stripes, a biomimetic segmented reflective coating strategy is proposed, and its building thermal performance is evaluated in a certain urban area of Panama City. Research has shown that sloping roofs designed with reflectivity contrast stripes exhibit better thermal regulation performance than total reflection roofs. The heterogeneous reflective coating enhances local radiative heat dissipation and promotes natural convection, synergistically optimizing the thermal regulation capability of building envelope structures.Guo et al[75]Inspired by the superhydrophobic surface of lotus leaves, a biomimetic multi-level structure thermal barrier coating was developed using plasma spray physical vapor deposition with multi-level micro nano structures.Mugdha et al[76]Several studies on the construction of superhydrophobic coatings using biomass materials such as lignin, cellulose, chitosan, and starch were introduced, as well as the techniques used to construct superhydrophobic coatings.

## 2.3 Transparent coating

Due to the drawbacks of high solar transmittance, poor thermal insulation, and low thermal inertia of transparent building envelope structures, and the fact that the heat transfer coefficient of traditional glass is often higher than that of walls with insulation layers, it is easy to form a "cold bridge" inside the building, resulting in energy loss of transparent building envelope structures accounting for about 60% of the total energy loss[83][84].This means that the transparent enclosure structure is the weakest link in building insulation. In recent years, academia has developed transparent thermal insulation coatings with more energy-saving potential by using sol gel method, hydrothermal method and filler modification.Virtudazo et al[85]NHSPs nano hollow silicate particles were prepared by soft template sol gel method. The internal air layer was used to prevent heat insulation and conduction, and nano particles stacked to inhibit convective heat transfer. After coating, the thermal conductivity of the glass substrate was reduced by 29.9% and remained transparent.Bao et al[86]The size adjustable double-layer hollow was successfully prepared by sol-gel method $TiO_2@SiO_2$ Microspheres were combined with waterborne polyurethane to prepare a new transparent insulating glass coating that maintains 85% visible light transmittance while increasing UV shielding to 98.7%.Zhang et al[87]The water-borne polyurethane (FWPU) base material with excellent water resistance was prepared by cross linking modification of multiple sealants, and further mixed with modified silica aerogel (SSA) to prepare a high water resistant transparent thermal insulation coating with a thermal conductivity of 0.1288W/(m • K), which significantly reduced the energy consumption of glass.Zhang et al[88]Silicon dioxide/antimony doped tin oxide was prepared by hydrothermal method ($SiO_2$@ATO) A transparent thermal insulation coating with a visible light transmittance of 83% was prepared by composite preparation of submicron hollow microspheres and acrylic resin.

## 3. Summarize

Traditional thermal insulation coatings—barrier-type (via sol-gel, in-situ polymerization, and solid-phase reactions to reduce thermal conductivity while enhancing high-temperature stability and sintering resistance), reflective-type (achieving high reflectivity and chromatic tunability through material modification), and radiative-type (improving emissivity via microsphere embedding and phase-change integration) — alongside emerging coatings, such as phase-change types (microencapsulation mitigating leakage yet suffering from thermal conductivity hysteresis and thermomechanical mismatch-induced microcracks), bioinspired types (lightweight, thermal-insulating, and hydrophobic synergies via hierarchical micro-nano bionic structures but limited by mechanical degradation of biomass-based materials and scalability bottlenecks), and transparent types (balanced optical-thermal performance via nano-hollow/aerogel composites yet constrained by cost-effectiveness of sol-gel synthesis and interfacial adhesion on flexible substrates), exhibit functional advancements.

However, both categories confront shared challenges: 1) Insufficient universality validation regarding substrate compatibility, weathering resistance, and environmental durability; 2) Economic and environmental constraints of critical processes, including import-dependent atomic layer deposition and energy-intensive processes (e.g., mechanical exfoliation, microsphere fabrication); 3) Scalability defects from non-uniform gravitational self-deposition and poor scalability of sintering processes; 4) Inadequate long-term service evaluation frameworks, necessitating multi-scenario accelerated aging and dynamic load fatigue testing protocols. Addressing these requires integrated optimization of material-process-service lifecycles to bridge laboratory innovations and industrial applications.

## 4. Prospect

Future research needs to continue to focus on breakthroughs in dynamic adaptive control technology, multi mechanism collaborative optimization, and low-carbon preparation processes, with a focus on developing intelligent responsive coatings and biomimetic composite systems to simultaneously address cost, durability, and extreme environmental adaptability issues, and promote the transformation of high-performance coatings from laboratory to engineering applications. At the same time, it is necessary to establish a full lifecycle carbon assessment system, promote green material substitution and process innovation, accelerate large-scale production and intelligent integration, and help achieve the goal of building carbon neutrality.

## References

[1] Liang Meicong, Qin Yuanyuan, Fan Xing, etc Interpretation of Main Conclusions and Suggestions for Countermeasures in the Third Working Group Report of IPCC Sixth Assessment Report [J]. Environmental Protection, 2022, 50 (13): 72-76. DOI: 10.14026/j.cnki. 0253-9705.2022.13.017.

[2] IPCC.Climate Change 2022 [M]. Mitigation of Climate Change Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press; Cambridge, UK and New York, NY, USA. 2022. https://www.ipcc.ch/report/sixth-assessment-report-working-group-3/.

[3] Wang G ,Luo T ,Luo H , et al.A comprehensive review of building lifecycle carbon emissions and reduction approaches[J].City and Built Environment,2024,2(1):12-12.

[4] Research Report on Energy Consumption and Carbon Emissions of Chinese Buildings (2022) [J]. Building, 2023 (2): 57-69.

[5] Song Tao Energy consumption analysis of public buildings in Urumqi area [D]. Xinjiang University, 2015.

[6] Hai Chenchen, Liu Xinzhi, Liu Xiaotong Overview of Application and Research Progress of Thermal Insulation Coatings [J]. New Materials Industry, 2020.

[7] Lu X, Xu P, Wang H, et al. Cooling potential and applications prospects of passive radiative cooling in buildings: The current state-of-the-art[J]. Renewable and Sustainable Energy Reviews, 2016, 65: 1079-1097.

[8] Raman A P, Anoma M A, Zhu L, et al. Passive radiative cooling below ambient air temperature under direct sunlight[J]. Nature, 2014, 515(7528): 540-544.

[9] Qiu Yuting, Wang Shuyu, Li Na, etc Research progress on insulation type multifunctional exterior wall coatings [J]. Contemporary Chemical Research, 2017, (05):104-105.DOI:10.20087/j.cnki.1672-8114.2017.05.060.

[10] Roland, Wang Shu, Wang Jian, etc Research progress on thermal insulation and fire-resistant building coatings [J]. Guangdong Chemical Industry, 2015, 42 (20): 5-6+26.

[11] Yang Wei Application of Thermal Insulation Coatings in Building Energy Efficiency [J]. Heilongjiang Science and Technology Information, 2010, (04): 271.

[12] Wang Wenwu, Yang Zhenguo, Chi Huachun Research Progress on Thermal Insulation Coatings [J]. Chemical Engineering and Equipment, 2018, (03):217-219.DOI:10.19566/j.cnki.cn35-1285/tq.2018.03.079.

[13] Ma Yiping, Yang Fan, Tan Chang, etc Research Status of Thermal Insulation Coatings [J]. Materials Review, 2015, 29 (S1): 300-304.

[14] Huang Jie, Zhang Song, Li Yong, etc Research and Prospect of Building Thermal Insulation and Cooling Coatings [J]. Shanghai Coatings, 2010, 48 (04): 30-33.

[15] Jin Tao, Liu Liqiang Application Status and Development of Thermal Insulation Coatings for External Walls [J]. New Building Materials, 2008, (06): 87-89.

[16] Yao Mengjia, Li Chunfu, He Junbo, etc Research, Development, and Application of Thermal Insulation Coatings [J]. Surface Technology, 2015, 44 (07): 61-67. DOI: 10.16490/j.cnki. issn. 1001-3660.2015.07.012.

[17] Jieyu W ,Donald P ,Shenqiang R .Transparent thermal insulation silica aerogels[J].NANOSCALE ADVANCES,2020,2(12):5504-5515.

[18] Xu L ,Jiang Y ,Feng J , et al.Infrared-opacified Al2O3–SiO2aerogel composites reinfor-ced by SiC-coated mullite fibers for thermal insulations[J].Ceramics International,2015,41(1):437-442.

[19] Lu A ,N. J A ,Yong H , et al.High temperature ceramic thermal insulation material[J].Nano Research,2022,15(7):6662-6669.

[20] Yang D ,Lixia Y ,Mengmeng Y , et al.Optimization of ultralight SiO2/TiO2 nanofibrous aerogel for high-temperature application[J].Ceramics International,2023,49(23PA):38058-38069.

[21] Mingkai L ,Jiaxuan L ,Xiongbang W , et al.Synergistic thermal insulation enhancement of an Al2O3/MnO2 @ fumed silica composite thermal insulation coating with high-temperature resistance up to 1200 °C[J].Materials Characterization,2024,207113568-.

[22] Zheng C, Hu D, Liu Z, et al. A simple and efficient in situ polymerization of silica xerogel-acrylic thermal insulation coatings[J]. Progress in Organic Coatings, 2024, 187: 108142.

[23] LI F ,ZHOU L ,LIU J , et al.High-entropy pyrochlores with low thermal conductivity for thermal barrier coating materials[J].Journal of Advanced Ceramics,2019,8(04):576-582.

[24] Yan Wei Preparation and Performance Study of Temperature resistant and Flame retardant Thermal Insulation Coating [D]. Central South University of Forestry and Technology, 2024. DOI: 10.27662/d.cnki.gznlc.2024.000848.

[25] Zhang S ,Wang W ,Gao Y , et al.Air pressure spray deposition of layer-by-layer cal-cium niobate nanosheets for efficient thermal insulation coatings[J].Ceramics International,2024,50(24PB):53899-53906.

[26] Deepa M J, Arunima S R, Elias L, et al. BiVO4–TiO2 composite-based zinc phosphate coating for high NIR reflectance and sustainable energy-saving applications[J]. Industrial & Engineering Chemistry Research, 2022, 61(19): 6481-6493.

[27] Soumya S, Mohamed A P, Paul L, et al. Near IR reflectance characteristics of PMMA/ZnO nanocomposites for solar thermal control interface films[J]. Solar energy materials and solar cells, 2014, 125: 102-112.

[28] Zhang L , Pei S B , Zhang M ,et al.Waterborne novolac epoxy-based thermal resistant and fire-retardant thermal insulation coatings[J].Journal of Applied Polymer Science, 2025, 142(2).DOI:10.1002/app.56360.

[29] Wang Lin,Xie Yongshuai,Liu Benxue,et al.Flexible TiO2 ceramic fibers near-infrared reflective membrane fabricated by electrospinning[J].CERAMICS INTERNATIONAL, 2019, 45(6).

[30] Kim H J, Kim D S, Mun H, et al. Shape control of rutile TiO2 particles templated u-sing graft copolymers for thermo-shielding materials[J]. Ceramics International, 2020, 46(1): 1227-1231.

[31] Huijun Y ,Zongwei T ,Baojie Z , et al.Thermal radiation shielded, high strength, fire resistant fiber/nanorod/aerogel composites fabricated by in-situ growth of TiO2 nanorods for thermal insulation[J].Chemical Engineering Journal,2021,418.

[32] Baojie Z ,Zongwei T ,Yifan P , et al.Design and electrospun closed cell structured SiO2 nanocomposite fiber by hollow SiO2/TiO2 spheres for thermal insulation[J].Composites Science and Technology,2022,218.

[33] Hong Yuanxiao Preparation and Research of Potassium Silicate Based Solar Heat Reflective Coating [D]. Southwest Jiaotong University, 2021. DOI: 10.27414/d.cnki.gxnju. 2021.002256.

[34] Liu C H, Lin H P. Synthesis of nano - sized TiO2/SiO2 cenospheres for the applicatio-n in high - performance solar thermal reflective coatings[J]. Journal of the Chinese Chemical Society, 2022, 69(8): 1495-1503.

[35] Ran J ,Lu X ,Kaixia Y , et al.Defect and interface co-steering ultra-wide microwave absorption and superior thermal conductance of TiO2/Fe/C nanocomposites[J].Applied Surface Science,2023,608

[36] Vuong T N ,Hung P D ,Anh T N , et al.Effects of nano-TiO2 and nano-SiO2 particles on the reflectance and weathering durability of solar heat reflectance coating[J].Journal of Photochemistry & Photobiology, A: Chemistry,2023,442.

[37] Chen Y ,Sha A ,Jiang W , et al.Eco-friendly bismuth vanadate/iron oxide yellow co-mposite heat-reflective coating for sustainable pavement: Urban heat island mitigation[J].Construction and Building Materials,2025,470140645-140645.

[38] Raj A K V, Rao P P, Sreena T S. Color tunable pigments with high NIR reflectance in terbium-doped cerate systems for sustainable energy saving applications[J]. ACS Sustainable Chemistry & Engineering, 2019, 7(9): 8804-8815.

[39] Raj A K V, Rao P P, Divya S, et al. Terbium doped Sr2MO4 [M= Sn and Zr] yellow pigments with high infrared reflectance for energy saving applications[J]. Powder technology, 2017, 311: 52-58.

[40] Tian M, Han A, Ma S, et al. Preparation of Cr-doped BaTiO3 near infrared reflection pigment powder and its anti-aging performance for acrylonitrile-styrene-acrylate[J]. Powder Technology, 2021, 378: 182-190.

[41] Chenlu C ,Aijun H ,Mingquan Y , et al.A new thermal insulation ceramic pigment: Ce-doped Y3Al5O12 compounds combined with high near-infrared reflectance and low thermal conductivity[J].Journal of Alloys and Compounds,2021,886.

[42] Feng L, Li L, Zhang M, et al. Novel and environment-friendly high NIR reflectance color pigments based on Fe, Pr, Ho, Nd, Er and Ce doped lithium aluminum molybdate: Synthesis and properties[J]. Ceramics International, 2022, 48(20): 30630-30639.

[43] Yu Maolin, Sun Hao, Yang Yucheng, etc Preparation and Thermal Insulation Performance of Reflective Blue Thermal Insulation Energy saving Coating [J]. Surface Technology, 2022, 51 (03): 217-225+295. DOI: 10.16490/j.cnki. issn. 1001-3660.2022.03.023.

[44] Lu Yiming be based on TiQ2@PA Preparation and performance of hybrid lotion reflective heat insulation coating [D]. South China University of Technology, 2023. DOI: 10.27151/d.cnki.ghnlu.2023.003296.

[45] Gomez-Gomez A, Ribas Gomes D, Winhard B F, et al. Mullite photonic glasses with exceptional thermal stability for novel reflective thermal barrier coatings[J]. Journal of Materials Science, 2023, 58(32): 12993-13008.

[46] Ragi T M, Francy A, Mohamed A P, et al. Processing of kaolin micro-composite functional fillers for enhancing the near-IR reflective performance of polyurethane resin coatings[J]. Applied Clay Science, 2024, 248: 107221.

[47] Qi Y ,Xiang B ,Zhang J .Effect of titanium dioxide (TiO2) with different crystal forms and surface modifications on cooling property and surface wettability of cool roofing materials[J].Solar Energy Materials and Solar Cells,2017,17234-43.

[48] Wang S, Zhang J, Liu L, et al. Evaluation of cooling property of high density polyethylene (HDPE)/titanium dioxide (TiO2) composites after accelerated ultraviolet (UV) irradiation[J]. Solar Energy Materials and Solar Cells, 2015, 143: 120-127.

[49] Mastai Y, Diamant Y, Aruna S T, et al. TiO2 nanocrystalline pigmented polyethylene foils for radiative cooling applications: synthesis and characterization[J]. Langmuir, 2001, 17(22): 7118-7123.

[50] Yi Y, Jiang Y, Li Q, et al. Development of super road heat-reflective coating and its field application. Coatings 9 (12): 802[EB/OL].(2019).

[51] Benkrima Y, Benhamida S, Belfennache D. Theoretical study of structural and optical properties of ZnO in wurtzite phase[J]. Digest Journal of Nanomaterials & Biostructures (DJNB), 2023, 18(1).

[52] Givoni B. Solar heating and night radiation cooling by a roof radiation trap[J]. Energy and buildings, 1977, 1(2): 141-145.

[53] Thomas N L, Wolfe J D. UV-shifted durable silver coating for astronomical mirrors[C]//Optical Design, Materials, Fabrication, and Maintenance. SPIE, 2000, 4003: 312-323.

[54] Jorgensen G J, Govindarajan R. Ultraviolet reflector materials for solar detoxification of hazardous waste[C]//Optical Materials Technology for Energy Efficiency and Solar Energy Conversion X. SPIE, 1991, 1536: 194-205.

[55] Brzezicki M. The architectural design of light-permeable facades–a summary of recent trends and observations[J]. Technical Transactions, 2019, 2019(Year 2019 (116)): 5-30.

[56] Shao G ,Wu X ,Cui S , et al.Design, formation, and property of high emissivity WSi2-Si-glass hybrid coating on fibrous ZrO2 ceramic for reusable thermal protection system[J].Solar Energy Materials and Solar Cells,2017,172301-313.

[57] Guoliang C ,Yaming W ,Jun Q , et al.Robust Inorganic Daytime Radiative Cooling Coating Based on a Phosphate Geopolymer.[J].ACS applied materials & interfaces,2020,12(49).

[58] Mishra B R, Sundaram S, Varghese N J, et al. Disordered metamaterial coating for daytime passive radiative cooling[J]. Aip Advances, 2021, 11(10).

[59] Mandal J, Fu Y, Overvig A C, et al. Hierarchically porous polymer coatings for highly efficient passive daytime radiative cooling[J]. Science, 2018, 362(6412): 315-319.

[60] Bo X ,Rong Z ,Yanlong L , et al.3D porous polymer film with designed pore archit-ecture and auto-deposited SiO2 for highly efficient passive radiative cooling[J].Nano Energy,2021,81105600-.

[61] Qing T ,Xitao T ,Liu Y , et al.Super-Large-Scale Hierarchically Porous Films Based on Self-Assembled Eye-Like Air Pores for High-Performance Daytime Radiative Cooling.[J].Small (Weinheim an der Bergstrasse, Germany),2022,18(51):e2205091-e2205091.

[62] Das P, Rudra S, Maurya K C, et al. Ultra-emissive MgO-PVDF polymer nanocomposite paint for passive daytime radiative cooling[J]. Advanced Materials Technologies, 2023, 8(24): 2301174.

[63] Guo C ,Li C ,Qiao Z , et al.Crack-Resistant and Self-Healable Passive Radiative Cooling Silicone Compounds.[J].Advanced materials (Deerfield Beach, Fla.),2025,e2500738.

[64] Principi P, Fioretti R. Thermal analysis of the application of pcm and low emissivity coating in hollow bricks[J]. Energy and Buildings, 2012, 51: 131-142.

[65] Wang Qinghua, Wang Ronghui, Wang Chunpeng Research on the Thermal Insulation Performance of Composite Phase Change Paraffin Hollow Block Walls [J]. New Building Materials, 2014, 41 (05): 56-59.

[66] Wu Taojun Preparation of Multi element Composite Phase Change Materials and Their Application in Building Energy Efficiency [D]. Shenyang Jianzhu University, 2015.

[67] Henghua Z ,Qianbin D ,Juetian L , et al.Modified sodium acetate trihydrate/expanded perlite composite phase change material encapsulated by epoxy resin for radiant floor heating[J].Journal of Energy Storage,2023,65.

[68] Shamshiri M, Jafari R, Momen G. An intelligent icephobic coating based on encapsulated phase change materials (PCM)[J]. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 2022, 655: 130157.

[69] Shi N N ,Tsai C ,Camino F , et al.Keeping cool: Enhanced optical reflection and radiative heat dissipation in Saharan silver ants[J].Science,2015,349(6245):298-301.

[70] Kulp F B , Liliana D , Shawkey M D ,et al.Keratin nanofiber distribution and feather microstructure in penguins[J].The Auk: Ornithological Advances, 2018, 135(3):777-787.

[71] Metwally S ,Comesaña M S ,Zarzyka M , et al.Thermal insulation design bioinspired by microstructure study of penguin feather and polar bear hair[J].Acta Biomaterialia,2019,91270-283.

[72] Zhan H J , Wu K J , Hu Y L ,et al.Biomimetic Carbon Tube Aerogel Enables Super-Elasticity and Thermal Insulation[J].Chem, 2019(5):1871-1882.DOI:10.1016/j.chempr.2019.04.025.

[73] Yeh-Liu L K , Hsu S Y , Chen P Y ,et al.Improvement of CrMoN/SiNx coatings on mechanical and high temperature Tribological properties through biomimetic laminate-d structure design[J].Surface and Coatings Technology, 2020, 393:125754.DOI:10.1016/j.surfcoat.2020.125754.

[74] Miguel A C ,Kevin A ,Paola P , et al.Numerical Assessment of Zebra-Stripes-Based Strategies in Buildings Energy Performance: A Case Study under Tropical Climate.[J].Biomimetics (Basel, Switzerland),2022,7(1):14-14.

[75] Yiqian G ,Wenjia S ,Lei G , et al.Molten-Volcanic-Ash-Phobic Thermal Barrier Coating based on Biomimetic Structure.[J].Advanced science (Weinheim, Baden-Wurttemberg, Germany),2023,10(10):e2205156-e2205156.

[76] Shigrekar M ,Amdoskar V .A review on recent progress and techniques used for fabr-icating superhydrophobic coatings derived from biobased materials.[J].RSC advances,2024,14(44):32668-32699.

[77] Dong L ,Ruitong Y ,Müslüm A , et al.Incorporating phase change materials into glazing units for building applications: Current progress and challenges[J].Applied Thermal Engineering,2022,210.

[78] Zhao X ,Sheng M ,Tang H , et al.A Flexible Electrochromic Device for All-Season Thermal Regulation on Curved Transparent Building Envelopes.[J].ACS applied materials & interfaces,2024.

[79] Virtudazo ,Rivera V R,Lin , et al.Synthesis and characterization of geometrically tunable nano-size hollow silicate particles and their dip-coating prepared films for thermal management applications[J].RSC Advances,2015,5(126):104408-104416.

[80] Yan B ,Ruyue G ,Qiaoling K , et al.Transparent, thermal insulation and UV-shielding coating for energy efficient glass window[J].Ceramics International,2021,47(17):24597-24606.

[81] Zhiyi Z ,Xiaofei H ,Lan J , et al.Highly water-resistant transparent waterborne polyurethane thermal-insulation coating material with multiple self-crosslinking network based on controllably activated end-capping reagent[J].Progress in Organic Coatings,2024,187108104-.

[82] Zhang Y ,Chen Y ,Li S , et al.Emerging SiO2@ATO hierarchical submicron hollow microspheres with efficient photo-thermal shielding properties[J].Materials Today Communications,2024,41110790-110790.