

Research on the Development of Thermal Insulation Mortar

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ABSTRACT

Building energy consumption accounts for approximately 35%–40% of global total energy use, making the improvement of envelope thermal performance a key strategy for building energy efficiency. Thermal insulation mortar has been widely used in building energy renovation due to its convenient construction, relatively low cost, and good compatibility with substrate walls. Although traditional lightweight aggregate thermal insulation mortars (e.g., expanded perlite, glazed hollow beads, EPS particles) can reduce thermal conductivity, they suffer from high water absorption, low compressive strength, drying shrinkage cracking, and insufficient long-term durability, which limit their application in high-performance energy-saving systems. In recent years, research has increasingly shifted toward aerogel-based thermal insulation cementitious composites. Aerogel, featuring a nanoporous structure, ultra-low density, and extremely low thermal conductivity, significantly reduces the thermal conductivity of mortar, enabling lightweight and highly efficient thermal insulation. However, the incorporation of aerogel also leads to a marked decline in mechanical properties, primarily due to the low strength of aerogel itself and the weak interfacial bonding between its hydrophobic surface and the cement paste, which tends to form interfacial transition zone defects and pore-rich regions. To address these challenges, researchers have focused on several aspects, including mix proportion design to balance thermal and mechanical performance by adjusting aerogel content, water-to-binder ratio, and admixtures; interface modification using silane coupling agents, dispersion aids, and low-shear mixing to improve compatibility and dispersion uniformity between aerogel and the cement matrix; fiber reinforcement through the introduction of polypropylene (PP), PVA, basalt and other fibers to bridge cracks, enhance toughness, and compensate for strength loss and cracking tendency; and multi-performance synergistic evaluation extending from single thermal conductivity testing to comprehensive assessments covering water absorption, drying shrinkage, freeze–thaw cycling, high-temperature stability, crack resistance, and long-term durability. Furthermore, international research has extended aerogel thermal insulation mortar to fire resistance and extreme environment applications, such as tunnel fire protection, industrial insulation, and structural thermal protection under high temperatures. Overall, research on thermal insulation mortar has evolved from traditional lightweight aggregate systems toward aerogel-based high-performance composites, with the focus shifting from simply reducing thermal conductivity to synergistic optimization of thermal, mechanical, and durability properties. Nevertheless, challenges remain in terms of high aerogel cost, insufficient interfacial bonding, difficulties in large-scale preparation, and lack of engineering application standards. Future research should focus on low-cost aerogel production, interface strengthening, multiphase composite reinforcement, long-term service performance evaluation, and construction technique optimization, so as to promote the transformation of thermal insulation mortar toward a multi-functional integration of thermal insulation, crack resistance, durability, and structural compatibility.

KEYWORDS

Thermal insulation mortar; Aerogel; Thermal conductivity; Mechanical properties; Interface modification; Durability

1. CURRENT STATE OF DOMESTIC RESEARCH

In recent years, with the continuous improvement of building energy efficiency standards in China, thermal insulation mortars have attracted extensive attention in the field of building envelope systems. Traditional insulation mortars are mainly composed of lightweight aggregates such as expanded perlite, vitrified microbeads, vermiculite, and polystyrene particles, which reduce thermal conductivity by increasing porosity and decreasing bulk density [1–3]. These materials have advantages such as convenient construction, relatively low cost, and good compatibility with wall substrates. However, they still suffer from several limitations, including high water absorption, low mechanical strength, drying shrinkage cracking, and insufficient long-term durability [4–5].

In recent years, research focus in China has gradually shifted from traditional lightweight aggregate mortars to high-performance composite insulation mortars. Among them, aerogel-based insulation mortars have become a research hotspot due to their ultra-low density, high porosity, and extremely low thermal conductivity [6–7]. The nanoporous structure of aerogels can effectively suppress solid conduction, gas conduction, and convective heat transfer, significantly improving thermal insulation performance. Studies have shown that incorporating silica aerogel into cement-based materials can greatly reduce thermal conductivity, making them promising candidates for high-performance insulation systems [6].

From the perspective of material design, Chinese researchers mainly focus on mix proportion optimization, thermal performance improvement, mechanical enhancement, and durability evaluation. Increasing aerogel content generally leads to lower density and thermal conductivity, but it also results in reduced compressive and flexural strength due to the weak mechanical properties of aerogel and poor interfacial bonding with cement matrices [8–9]. Therefore, achieving a balance between thermal insulation and mechanical performance remains a key research issue.

To address interfacial compatibility problems, various modification methods have been proposed, such as silane coupling treatment, dispersant-assisted mixing, and incorporation of mineral admixtures to improve the bonding between aerogel particles and cementitious matrices [10–11]. These approaches help reduce agglomeration and enhance interfacial transition zones, thereby improving overall performance. Furthermore, studies indicate that multi-phase composite design and interface engineering are essential strategies to achieve synergistic improvements in thermal insulation, flame retardancy, and mechanical stability.

In addition, fiber reinforcement techniques have been widely adopted to compensate for the strength loss caused by aerogel incorporation. Fibers such as polypropylene, PVA, and basalt fibers can effectively bridge cracks, improve toughness, and enhance crack resistance [12–13]. However, excessive fiber content may adversely affect workability and increase porosity, requiring careful optimization.

In terms of durability, research in China has gradually expanded from basic thermal and mechanical properties to comprehensive performance evaluation, including water absorption, drying shrinkage, freeze–thaw resistance, and high-temperature stability [14–15]. It has been recognized that insulation mortars are exposed to complex environmental conditions, and their long-term performance must be systematically evaluated. Current studies also highlight that large-scale application of aerogel-based materials still faces challenges such as high cost, manufacturing complexity, and insufficient long-term reliability under extreme conditions.

Overall, research in China has evolved from traditional lightweight insulation mortars to advanced multifunctional composite systems. Future work should focus on low-cost aerogel production, interface optimization, fiber reinforcement, and long-term durability evaluation to achieve multifunctional integration of insulation, mechanical strength, and durability.

2. CURRENT STATUS OF RESEARCH ON INSULATING MORTAR ABROAD

Research on thermal insulation mortars abroad started earlier and is closely related to the global demand for energy-efficient buildings. It is estimated that buildings account for approximately 35–40% of total energy consumption worldwide, making thermal insulation of building envelopes a critical issue [16]. Early studies mainly focused on lightweight aggregate mortars using expanded perlite, expanded glass, and polymer particles to reduce thermal conductivity [17–18]. However, these materials have limited insulation efficiency and durability, prompting the development of advanced insulation materials.

In recent years, aerogel-based cementitious composites have become a major research focus due to their superior thermal insulation properties. Aerogels possess extremely low thermal conductivity, often lower than that of still air, due to their nanoscale porous structure [19–20]. Koebel et al. [19] and Pierre et al. [20] demonstrated that aerogels are among the most effective superinsulation materials. Adhikary et al. [16] further reviewed their applications in cement-based materials, highlighting their potential in plastering mortars, insulation panels, and lightweight concretes.

Numerous studies have confirmed that the addition of aerogels significantly reduces thermal conductivity while decreasing density. Gao et al. [21] showed that increasing aerogel content leads to a substantial reduction in thermal conductivity, while Ng et al. [22] reported similar findings in ultra-high-performance concrete. However, this improvement in thermal performance is often accompanied by a reduction in mechanical strength due to the weak structure of aerogels and poor interfacial bonding [23].

To overcome these issues, extensive research has been conducted on surface modification and dispersion techniques. Silane coupling agents, chemical treatments, and optimized mixing methods have been used to improve compatibility between aerogels and cement matrices [24–25]. Additionally, hybrid systems incorporating fibers or other lightweight aggregates have been developed to enhance mechanical performance and structural integrity [23, 26].

Durability has also become a major concern in recent studies. Aerogel incorporation alters pore structure, which may increase water absorption and affect long-term stability [16, 27]. Therefore, researchers have expanded evaluation criteria to include freeze–thaw resistance, moisture effects, and high-temperature performance. Studies indicate that aerogel-based mortars can provide effective thermal protection under high-temperature conditions, making them suitable for fire-resistant applications [27].

Moreover, aerogel-based insulation mortars have been extended to extreme environment applications, including fire protection, industrial insulation, and energy systems. Their ability to significantly reduce heat transfer makes them promising for improving structural safety in fire scenarios and enhancing thermal management in advanced engineering systems [16, 18].

In summary, international research has evolved from traditional lightweight mortars to high-performance aerogel-based composites, with a strong emphasis on multi-functional performance optimization. Despite significant progress, challenges such as high material cost, weak interfacial bonding, and large-scale production remain key issues for future development.

REFERENCES

- [1] Zhang X., Li D., Wang Y., et al. Research progress of thermal insulation mortar. *Journal of Building Materials*, 2018, Vol. 21 (No. 3), p. 45–52.
- [2] Wang J., Liu W., Chen H., et al. Study on vitrified microbead insulation mortar. *New Building Materials*, 2019, Vol. 46 (No. 6), p. 78–83.

- [3] Chen J., Zhou M., Li Q., et al. Thermal performance of expanded perlite insulation mortar. *Bulletin of the Chinese Ceramic Society*, 2020, Vol. 39 (No. 5), p. 1523–1529.
- [4] Li Q., Zhang T., Sun Y., et al. Water absorption and durability of inorganic insulation mortar. *Concrete*, 2021, Vol. 12 (No. 4), p. 102–107.
- [5] Liu H., Wang Z., Zhao L., et al. Cracking mechanism and control of exterior insulation mortar. *Construction Technology*, 2020, Vol. 49 (No. 10), p. 95–99.
- [6] Pierre A.C., Pajonk G.M. Chemistry of aerogels and their applications. *Chemical Reviews*, 2002, Vol. 102 (No. 11), p. 4243–4265.
- [7] Koebel M., Rigacci A., Achard P., et al. Aerogel-based thermal superinsulation: an overview. *Journal of Sol-Gel Science and Technology*, 2012, Vol. 63 (No. 3), p. 315–339.
- [8] Gao T., Jelle B.P., Gustavsen A., et al. Aerogel-incorporated concrete: an experimental study. *Construction and Building Materials*, 2014, Vol. 52 (No. 1), p. 130–136.
- [9] Ng S., Jelle B.P., Sandberg L.I.C., et al. Experimental investigation of aerogel-incorporated ultra-high performance concrete. *Construction and Building Materials*, 2015, Vol. 77 (No. 1), p. 307–316.
- [10] Lu X., Wang P., Chen W., et al. Surface modification of silica aerogel and its influence on cement-based composites. *Construction and Building Materials*, 2019, Vol. 215 (No. 1), p. 452–460.
- [11] Zhu P., Li J., Xu L., et al. Hydrophobic silica aerogel cement-based thermal insulation mortar. *Cement and Concrete Composites*, 2020, Vol. 111 (No. 1), p. 103628.
- [12] Li V.C. Engineered cementitious composites (ECC): material, structural, and durability performance. *Concrete Construction Engineering Handbook*, 2008, Vol. 1 (No. 1), p. 1–38.
- [13] Zhang Y., Li V.C. Influence of fibers on cracking behavior of cementitious composites. *Cement and Concrete Research*, 2012, Vol. 42 (No. 11), p. 231–236.
- [14] Zhou Y., Li T.T., Ren H.T., et al. Recent advances in the application of typical organic aerogel materials for thermal protection. *Cotton Textile Technology*, 2026, Vol. 54 (No. 0), p. 1–11.
- [15] Zhang Q.R., Ma L., Xue T.T., et al. Flame-retardant and thermal-protective polyimide aerogel fiber-based composite textile for firefighting clothing. *Composites Part B: Engineering*, 2023, Vol. 248 (No. 1), p. 110377.
- [16] Adhikary S.K., Ashish D.K., Rudžionis Ž., et al. Aerogel-based thermal insulating cementitious composites: a review. *Energy and Buildings*, 2021, Vol. 245 (No. 1), p. 111058.
- [17] Gurav J.L., Jung I.K., Park H.H., et al. Silica aerogel: synthesis and applications. *Journal of Nanomaterials*, 2009, Vol. 2009 (No. 1), p. 1–11.
- [18] Maleki H., Durães L., Portugal A., et al. Silica aerogels: properties and applications. *Journal of Non-Crystalline Solids*, 2014, Vol. 385 (No. 1), p. 55–74.
- [19] Hüsing N., Schubert U., et al. Aerogels—airy materials: chemistry, structure, and properties. *Angewandte Chemie International Edition*, 1998, Vol. 37 (No. 1–2), p. 22–45.
- [20] Pierre A.C., Pajonk G.M., et al. Aerogel chemistry and applications. *Chemical Reviews*, 2002, Vol. 102 (No. 11), p. 4243–4265.
- [21] Gao T., Jelle B.P., Gustavsen A., et al. Thermal performance of aerogel-based concrete materials. *Construction and Building Materials*, 2014, Vol. 52 (No. 1), p. 130–136.
- [22] Ng S., Jelle B.P., Sandberg L.I.C., et al. Aerogel-incorporated UHPC performance study. *Construction and Building Materials*, 2015, Vol. 77 (No. 1), p. 307–316.
- [23] Hanif A., Diao S., Lu Z., et al. Properties investigation of cement-based composites incorporating aerogel. *Construction and Building Materials*, 2016, Vol. 120 (No. 1), p. 587–596.
- [24] Kim S., Seo J., Cha J., et al. Chemical retreatment of silica aerogel for cementitious composites. *Journal of Sol-Gel Science and Technology*, 2018, Vol. 86 (No. 2), p. 343–350.
- [25] Lu X., Wang P., Chen W., et al. Interface modification of aerogel composites. *Construction and Building Materials*, 2019, Vol. 215 (No. 1), p. 452–460.
- [26] Shah S.N., Qureshi L.A., et al. Aerogel-based cement composites: a comprehensive review. *Journal of Building Engineering*, 2021, Vol. 44 (No. 1), p. 102627.
- [27] Al-Zaidi A., Demirboğa R., et al. Mechanical and thermal properties of aerogel-based cement composites. *Construction and Building Materials*, 2019, Vol. 199 (No. 1), p. 191–200.