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Miraculous Versatile Radiative Cooling Cement for Sustainable Buildings

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Abstract

The development of daytime passive radiative cooling materials represents a pivotal approach for reducing energy consumption in building cooling and carbon emissions. In a recent issue of *Science Advances*, Lu *et al*. reported a scalable supercool cement, which achieves significant radiative cooling through a cleverly designed metasurface structure without relying on external additives or high energy consuming processing. This study presents a scalable pathway for the transformation of traditional cement into a versatile and intelligent energy-efficient building material.

Keywords: Radiative cooling; Energy-efficient buildings; Zero energy consumption; Cement materials.

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Cooling energy consumption constitutes over 60% of the building energy consumption and generates a substantial amount of carbon emissions,[1] intensifying the urban heat island effect and seriously hindering the global deep decarbonization process. Therefore, developing a power-free building cooling solution is of great significance for promoting the transformation of the global energy structure and ensuring sustainable development. Daytime passive radiative cooling (PDRC) technology has the capacity to effectively lower the surface temperature of objects through sunlight reflection (0.25-25 μm) and thermal infrared radiation emission (8-13 μm).[2-4] With the characteristics of zero energy consumption and zero emissions, this technology holds great promise in reducing global energy consumption. It has already demonstrated remarkable potential in various fields, including photovoltaic cooling and personal thermal management, and has also drawn extensive attention within the domain of energy-efficient buildings.[5] In recent years, a series of emerging radiative cooling materials, such as polymer-based coatings and radiative cooling ceramics, have been developed successively.[6-8] Although radiative cooling ceramics possess excellent optical properties and thermal stability, their preparation often relies on energy-intensive sintering processes. Moreover, integrating them seamlessly with building substrates remains a challenge. Likewise, while polymer-based cooling coatings are easy to process, when applied to building envelopes, the poor interfacial adhesion often leads to coating delamination or functional failure. Additionally, secondary processing or functional coatings incur additional energy costs. These factors collectively restrict their large-scale application in the building field.

Traditional cement, recognized as the engineering material with the highest global production output and the broadest application scope, demonstrates commendable infrared emission capabilities and structural stability.[9,10] It harbors latent advantages in being converted into radiative cooling materials. Consequently, it holds promise in addressing the issues of interface bonding and durability between radiative cooling materials and building wall surfaces. Nevertheless, its relatively low solar reflectance (approximately 30%) still poses a central challenge. Most of the existing studies endeavor to rectify the low reflectivity of traditional cement by either applying coatings or incorporating functional particles.[11,12] Regrettably, these approaches often come at the expense of structural integrity and energy efficiency. Fundamentally speaking, the key strategy for achieving large-scale sustainable cooling lies in transcending current "quick-fix" approaches. Instead, efforts should be directed towards enhancing the inherent reflective capabilities of the cement matrix itself. This approach aims to develop high-efficiency cooling materials that are coeval with the building structure

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and consume minimal energy.

In a recent breakthrough released in *Science Advances*,[13] Guo Lu, Wei She, Changwen Miao, and their co-researchers devised a novel supercool cement. This innovation aims to drive a negative-carbon transition in the construction sector and contribute to the successful attainment of dual-carbon goals. The uniqueness of this work lies in its comprehensive consideration from material synthesis to practical application while maintaining the inherent structural characteristics of cement. The authors employed calcium-rich alumina-sulfur-silicate compounds for the cement clinkers and adopted a gas difference-driven cavitation strategy. Using polydimethylsiloxane (PDMS) molds with concave micro-cylinders, they nano-engineered the material to fabricate hexagonally arranged microcavities on the surface (Fig. 1A). As a result, a cement-based radiative cooler integrated with an optical metasurface was developed (Fig. 1B). The constructed microcavity structure promoted the self-assembly of highly reflective ettringite crystals on the surface, enhancing light scattering (Fig. 1C). This enabled the cement to exhibit high solar reflectance (96.2% on average). Meanwhile, the inherent infrared-active functional groups in the cement hydration products (such as Al-O and Ca-O bonds) were retained (Fig. 1D), leading to a high mid-infrared emissivity (96.0%) (Fig. 1E). This material is compatible with existing industrial processes such as rotary kiln production and roll-to-roll manufacturing, highlighting its scalability (Fig. 1F). It also demonstrates excellent compressive strength (exceeding 100 MPa), wear resistance, and stability under UV exposure, freeze-thaw cycles (Fig. 1G), and corrosive conditions. When the supercool cement cast as coatings, it shows high adhesive strength to various materials, including concrete, metals, and ceramic tiles. Furthermore, the research team demonstrated its superamphiphobicity (Fig. 1H), antifouling properties (Fig. 1I), and color aesthetics by incorporating hydrophobic modifiers and fluorescent dyes, while maintaining cooling performance.

In practical outdoor tests, this supercool cement can achieve a cooling effect of 5.4 °C lower than the ambient temperature under direct sunlight, which is 26 °C lower than that of commercial cement (Fig. 1J). The authors conducted a life cycle assessment utilizing machine learning and estimated that each ton of supercool cement could reduce carbon dioxide emissions by up to 2,867.78 kg over a 70-year service life compared to ordinary Portland cement in Niamey. (Fig. 1K). In climatic conditions like those in Niamey or Chongqing, the building envelope constructed with this cement might offset the embodied carbon in the production process within decades, achieving net-zero or even negative net carbon. This offers a robust technical approach for the sustainable development of the global construction industry and the realization of carbon neutrality objectives.

The profound significance of this study lies in redefining the role of traditional cement. It has shifted from being an inherent source of high carbon emissions to a multifunctional material with both cooling capabilities and negative carbon potential. Based on this, the further development of supercool cement is of utmost importance for realizing the vision of scalable and multifunctional intelligent energy-efficient building thermal interaction. Firstly, supercool cement can be integrated with photovoltaic systems to achieve a synergistic effect between building energy generation and cooling. Such integration can optimize energy consumption and the thermal environment within buildings, thereby enhancing overall energy efficiency. Secondly, develop intelligent temperature-regulating building envelopes integrated with phase-change materials or thermochromic materials. These building envelopes can sense the changes in the surrounding temperature like the skin of the human body and autonomously adjust their own properties to maintain a comfortable indoor environment. Thirdly, harness the power of artificial intelligence (AI) to expedite material design and precisely modulate material performance through the integration of self-cleaning properties, aesthetic color, flame retardancy, and sound insulation performance. AI-driven algorithms can analyze vast amounts of data, significantly reducing the costs associated with manual trial and error processes. This capability facilitates more accurate prediction and control of the synergistic interactions among diverse material properties, ultimately enabling the development of more advanced intelligent energy-efficient building materials. Finally, deploy the use of materials at the urban level to mitigate the urban heat island effect. The application of this novel supercool cement in urban construction can effectively lower the surface temperature of buildings and urban infrastructure, thereby alleviating the overall heat accumulation in cities. From a long-term perspective, incorporating functional components such as advanced hydrophobic materials or phase change materials may increase production costs compared to traditional cement. Nevertheless, from a cost-effectiveness standpoint, despite the relatively high initial investment, the long-term benefits, encompassing reduced cooling and heating energy consumption, decreased building cleaning and maintenance expenses, and alleviation of the urban heat island effect, have the potential to offset the upfront costs throughout the life cycle. Realizing this vision necessitates interdisciplinary collaboration across materials science, artificial intelligence, urban design, and policy-making. Supercool cement represents a pivotal breakthrough en route to this sustainable future.

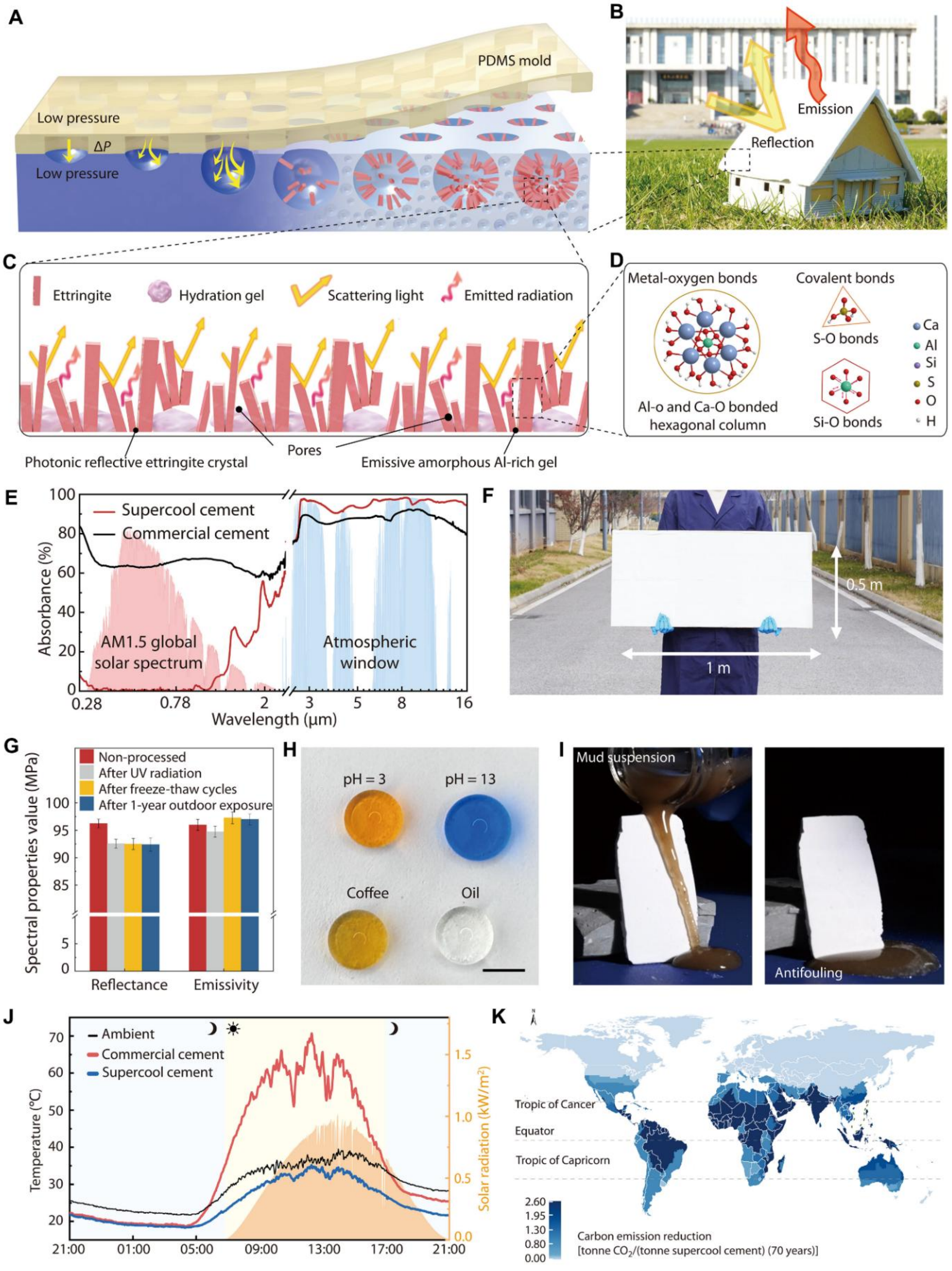

Fig. 1: Scalable versatile supercool cement. A) Surface engineering strategy during the hydration process of supercool cement. B) Supercool cement used for building roofs. C) Self-assembly of high-reflectivity ettringite crystal hydration products on the surface of microcavities. D) Infrared active vibration modes of Al-rich, Ca, Si and S functional groups. E) Spectral absorptance of supercool cement; background shows AM 1.5 solar irradiance and atmospheric window. F) Large-area supercool cement slabs. G) Variations in optical properties following environmental aging. H) Superamphiphobicity of supercool cement. I) Antifouling properties of supercool cement. J) All-day subambient cooling performance of the supercool cement. K) Heat map of the CO_2 emission reduction potential of cities around the world. Reproduced with permission from Lu *et al*.[13] Copyright 2025, AAAS.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

CRediT Statement

Bingying Liu: Writing, Original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation.
Chaohua Xue: Supervision, Resources, Funding acquisition.

References

[1] G. Tregnago, Cool shadings, *Nature Energy*, 2023, **8**, 771, doi: 10.1038/s41560-023-01346-0.

[2] D. Shou, Z. Li, Sustainable personal cooling in a warming world, *Science*, 2025, **389**, 877-878, doi: 10.1126/science.adt9536.

[3] C. Xiao, M. Liu, K. Yao, Y. Zhang, M. Zhang, M. Yan, Y. Sun, X. Liu, X. Cui, T. Fan, C. Zhao, W. Hua, Y. Ying, Y. Zheng, D. Zhang, C. Qiu, H. Zhou, Ultrabroadband and band-selective thermal meta-emitters by machine learning, *Nature*, 2025, **643**, 80-88, doi: 10.1038/s41586-025-09102-y.

[4] Q. Zhang, Z. Chen, Q. Zhang, Y. Gao, Glacier defense: a material science proposal, *Engineered Science*, 2025, **36**, 1692, doi: 10.30919/es1692.

[5] H. Chen, X. Liu, J. Liu, F. Wang, C. Wang, Radiative cooling applications toward enhanced energy efficiency: System designs, achievements, and perspectives, *The Innovation*, 2025, **6**, 100999, doi: 10.1016/j.xinn.2025.100999.

[6] Y. Chen, J. Mandal, W. Li, A. Smith-Washington, C. C. Tsai, W. Huang, S. Shrestha, N. Yu, R. P. S. Han, A. Cao, Y. Yang, Colored and paintable bilayer coatings with high solar-infrared reflectance for efficient cooling, *Science Advances*, 2020, **6**, eaaz5413, doi: 10.1126/sciadv.aaz5413.

[7] X. Zhao, T. Li, H. Xie, H. Liu, L. Wang, Y. Qu, S. C. Li, S. Liu, A. H. Brozena, Z. Yu, J. Srebric, L. Hu, A solution-processed radiative cooling glass, *Science*, 2023, **382**, 684-691, doi: 10.1126/science.adi2224.

[8] K. Lin, S. Chen, Y. Zeng, T. C. Ho, Y. Zhu, X. Wang, F. Liu, B. Huang, C. Y. Chao, Z. Wang, C. Y. Tso, Hierarchically structured passive radiative cooling ceramic with high solar reflectivity, *Science*, 2023, **382**, 691-697, doi: 10.1126/science.adi4725.

[9] P. J. M. Monteiro, S. A. Miller, A. Horvath, Towards sustainable concrete, *Nature Materials*, 2017, **16**, 698-699, doi: 10.1038/nmat4930.

[10] S. A. Walling, J. L. Provis, Magnesia-based cements: a journey of 150 years, and cements for the future? *Chemical Reviews*, 2016, **116**, 4170-4204, doi: 10.1021/acs.chemrev.5b00463.

[11] D. Feng, A. S. Witty, F. I. Birnbaum, O. G. R. Gonzalez, A. Felicelli, W. J. Lee, E. C. Barber, X. Ruan, Self-stratifying colored radiative cooling paints through narrow-band color preservation scheme, *Advanced Materials*, 2025, e04382, doi: 10.1002/adma.202504382.

[12] J. Fei, X. Zhang, D. Han, Y. Lei, F. Xie, K. Zhou, S. W. Koh, J. Ge, H. Zhou, X. Wang, X. Wu, J. Y. Tan, Y. Gu, Y. Long, Z. H. Koh, S. Wang, P. Du, T. Mi, B. F. Ng, L. Cai, C. Feng, Q. Gan, H. Li, Passive cooling paint enabled by rational design of thermal-optical and mass transfer properties, *Science*, 2025, **388**, 1044-1049, doi: 10.1126/science.adt3372.

[13] G. Lu, F. Du, Z. Wang, F. Wu, W. Zuo, X. Xu, Z. Wu, C. Liu, R. Yang, Y. Tian, Z. Hu, D. Zhao, C. Guo, T. Li, W. She, C. Miao, Scalable metasurface-enhanced supercool cement, *Science Advances*, 2025, **11**, eadv2820, doi: 10.1126/sciadv.adv2820.

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