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HYDRO CERAMIC MATERIALS: A REVIEW OF THEIR ROLE IN SUSTAINABLE PASSIVE COOLING

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ABSTRACT

The increasing energy demand associated with conventional mechanical cooling systems has intensified the need for sustainable passive cooling solutions in the built environment. Hydro ceramic materials, which combine porous ceramic matrices with moisture-driven evaporative cooling mechanisms, have emerged as promising candidates for low-energy thermal regulation. This review systematically examines existing research on hydro ceramic and porous ceramic-based materials used for passive cooling applications. Emphasis is placed on material characteristics such as porosity, capillary water absorption, moisture retention, and surface wettability, which govern evaporative cooling performance. The reviewed studies demonstrate that hydro ceramic systems can achieve significant reductions in surface and ambient air temperatures under suitable environmental conditions without external energy input. The findings highlight the potential of hydro ceramic materials for integration into building envelopes to enhance thermal comfort and reduce cooling energy demand. This review consolidates current knowledge on hydro ceramic passive cooling systems and provides a technical basis for future material optimization and large-scale implementation in sustainable building design.

CHAPTER 1

INTRODUCTION

The accelerating pace of urbanization and the growing demand for thermal comfort have led to a substantial increase in energy consumption within the building sector. Buildings account for a significant share of global energy use, with cooling systems contributing considerably to peak electricity demand, particularly in regions with warm climatic conditions. This growing dependence on mechanical air-conditioning systems has raised serious concerns regarding energy sustainability, greenhouse gas emissions, and long-term environmental impact. Consequently, the development of energy-efficient and environmentally responsible cooling strategies has become a critical focus in contemporary building research.

Passive cooling techniques have emerged as viable alternatives to conventional active systems, as they utilize natural processes such as ventilation, shading, thermal mass, and evaporative cooling to regulate indoor temperatures without external energy input. Among these approaches, material-based passive cooling solutions have gained increasing attention due to their potential for seamless integration into building envelopes. Advanced materials capable of responding to environmental conditions and facilitating heat exchange offer promising pathways toward sustainable thermal regulation.

Hydro ceramic materials represent an emerging class of passive cooling materials that combine porous ceramic substrates with water-retentive components, such as hydrogels, to achieve evaporative cooling. These materials function by absorbing water within their porous structure and releasing it gradually through evaporation when exposed to elevated temperatures. The phase change process absorbs latent heat from the surrounding environment, resulting in a localized cooling effect. Owing to their passive operation, hydro ceramic materials do not require electricity during use and generate minimal environmental impact, making them particularly attractive for sustainable building applications.

In recent years, research efforts have explored the development, fabrication, and performance evaluation of hydro ceramic systems in architectural and material science contexts. Experimental studies and simulation-based analyses have demonstrated their potential to reduce surface and ambient temperatures, thereby lowering cooling energy demand when integrated into façades, walls, or shading elements. However, existing studies are fragmented, often focusing on isolated aspects such as material composition, water absorption behavior, or short-term thermal performance. Comprehensive reviews that critically examine the collective role of hydro ceramic materials in sustainable passive cooling remain limited.

Therefore, this review paper aims to synthesize and critically analyze existing literature on hydro ceramic materials, with a focus on their material characteristics, working mechanisms, thermal performance, advantages, limitations, and applicability in sustainable passive cooling systems. By identifying key research trends and gaps, this study seeks to provide a consolidated understanding of hydro ceramic technology and its potential contribution to energy-efficient building design, thereby supporting future research and practical implementation.

Objectives of the Study

1. Review existing research on hydro ceramic and porous ceramic materials used for passive cooling applications.
2. Examine the role of material properties such as porosity and water absorption in evaporative cooling performance.
3. Summarize the effectiveness of hydro ceramic materials in achieving sustainable passive cooling in buildings.

CHAPTER 2

LITERATURE REVIEW

Ibrahim, Shao, and Riffat (2003) conducted one of the early experimental studies on the performance of porous ceramic evaporators for building cooling applications. Their work investigated the ability of ceramic media to reduce air temperature through direct evaporative cooling under controlled conditions. The study demonstrated that porous ceramic structures could achieve notable dry-bulb temperature reductions when adequate water supply and airflow were provided, highlighting the feasibility of ceramic-based passive cooling systems.

He and Hoyano (2010) further advanced this concept by developing a Passive Evaporative Cooling Wall (PECW) using porous ceramic materials. Their experimental investigation focused on capillary water transport, surface wetting behavior, and airflow interaction under outdoor conditions. The results showed that ceramic walls with high water-soaking capacity could maintain wetted surfaces and reduce wall surface temperatures through evaporation. This study emphasized the importance of material porosity and environmental factors in determining cooling effectiveness

Jin et al. (2024) investigated humidity-controlling ceramic bricks designed to enhance evaporative cooling and mitigate urban heat island effects. Their study focused on optimizing ceramic microstructure and capillary absorption properties to improve water retention and evaporation rates. The results demonstrated measurable surface temperature reductions and sustained cooling effects, reinforcing the role of engineered ceramics in passive thermal regulation.

Yin et al. (2025) examined bilayer passive cooling materials integrating moisture-retentive layers with solar-reflective surfaces. Their work demonstrated that combining evaporative and radiative cooling mechanisms could significantly enhance passive cooling efficiency. While not specific to hydro ceramic materials, the study contributed to the broader understanding of multifunctional passive cooling material systems.

MATERIALS & METHODOLOGY

3.1 Materials Used in Hydro Ceramic Preparation

Hydro ceramic materials are composite materials designed to enable passive cooling through water absorption and evaporation. They are typically composed of porous ceramic matrices combined with moisture-retentive components. The main materials used in hydro ceramic preparation are described below.

3.1.1. Clay-Based Ceramic Materials

Natural clay is the primary raw material used in hydro ceramics. Common clays include kaolin, ball clay, and bentonite. These materials are selected for their ability to form a stable ceramic structure after firing while maintaining interconnected pores. The porous nature of fired clay allows water to be absorbed and transported to the surface through capillary action, which is essential for evaporative cooling.

3.1.2. Porosity-Forming Agents

To enhance water absorption and evaporation, porosity-forming agents are often added to the ceramic mixture. These may include sawdust, rice husk, starch, or polymeric pore formers. During the firing process, these additives burn out, leaving behind micro- and macro-pores that increase surface area and water-holding capacity.

3.1.3. Water-Retentive Materials

Some hydro ceramic systems incorporate moisture-retentive materials to improve water storage and prolong cooling duration. These materials may include hygroscopic compounds or water-absorbing polymers that can retain moisture within the ceramic matrix. Their function is to store water and release it slowly during evaporation.

3.1.4. Mineral Additives

Mineral additives such as silica, alumina, or grog may be included to improve mechanical strength, thermal stability, and durability. These additives help maintain structural integrity while preserving sufficient porosity for cooling performance.

3.1.5. Water

Water is a functional component of hydro ceramics. It is absorbed into the porous structure and evaporates from the surface, extracting heat from the surrounding environment. Continuous or periodic water supply is essential for sustained cooling performance.

3.2 Methodology

This study adopts a systematic literature review methodology to examine the role of hydro ceramic materials in sustainable passive cooling applications. Relevant research articles were identified from peer-reviewed journals focusing on porous ceramic materials, evaporative cooling systems, and passive cooling strategies for buildings.

The selection of literature was based on studies that experimentally or analytically evaluated ceramic-based evaporative cooling performance, including parameters such as water absorption capacity, evaporation rate, surface temperature reduction, and environmental influence. Only publications that reported measurable cooling outcomes were considered for review.

The selected studies were analyzed qualitatively to extract key information related to material composition, structural characteristics, cooling mechanisms, and performance results. Findings from individual studies were synthesized to identify common material features and cooling principles associated with hydro ceramic systems.

This review emphasizes experimentally validated results to assess the potential of hydro ceramic materials as sustainable alternatives to conventional mechanical cooling systems in the built environment.

RESULTS

The reviewed studies demonstrate that hydro ceramic materials are effective in providing sustainable passive cooling through evaporative mechanisms. Porous ceramic-based systems consistently showed the ability to reduce surface and ambient air temperatures when adequate moisture and airflow were available. The results indicate that high porosity and interconnected pore structures play a critical role in enhancing water absorption and sustaining evaporation.

Research on porous ceramic evaporators reported noticeable dry-bulb temperature reductions, confirming the feasibility of ceramic materials for passive cooling applications. Studies on passive evaporative cooling walls further revealed that ceramics with high water-soaking capacity maintained wetted surfaces and achieved lower wall surface temperatures under outdoor conditions. These findings highlight the suitability of hydro ceramic materials for building envelope applications.

Investigations into humidity-controlling ceramic bricks showed that optimized ceramic microstructures improved moisture retention and evaporation rates, resulting in prolonged cooling effects and reduced surface temperatures. Additionally, studies integrating moisture-retentive layers with other passive cooling strategies demonstrated enhanced cooling efficiency. Overall, the synthesized results confirm that hydro ceramic materials offer a low-energy, environmentally sustainable solution for passive cooling in the built environment.

CONCLUSION

This review establishes that hydro ceramic materials function as effective passive cooling media by coupling porous ceramic matrices with moisture-driven evaporative heat transfer mechanisms. The analyzed studies confirm that ceramics with high porosity, interconnected pore networks, and enhanced capillary water absorption can sustain surface wetting and promote continuous evaporation, resulting in measurable reductions in surface and ambient air temperatures. Thermal performance is strongly influenced by material microstructure, water retention capacity, and ambient climatic conditions. The findings indicate that hydro ceramic systems can significantly reduce cooling loads without external energy input, positioning them as viable components for low-energy building envelopes. Overall, hydro ceramic materials demonstrate strong potential for improving thermal regulation and energy efficiency in sustainable building applications.

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